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Informal STEM learning at home and in community spaces

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Informal STEM learning at home and in community spaces

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Editorial: Informal STEM learning at home and in community spaces

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Editorial on the Research Topic
Informal STEM learning at home and in community spaces

This Research Topic investigates how children's authentic, everyday experiences provide opportunities for STEM learning and engagement. Providing children with equitable opportunities to engage in, learn, and flex their STEM skills is critical because STEM drives new innovations across disciplines, accelerates discoveries, and finds creative ways to solve big challenges now and in the future (Fenechel and Schweingruber, 2010; Archer et al., 2022). But, what do we mean by informal STEM learning? We define "learning" broadly to include traditional definitions that focus on knowledge change and conceptual understanding, but we also include other areas supporting learning and connected to a more expansive definition, such as interest, engagement, and identity (see Fenechel and Schweingruber, 2010, for a detailed discussion). But why informal learning, in particular? This area is important because children spend only around 5% of their lives learning in formal settings (Falk and Dierking, 2010). Of that time, children are estimated to spend ∼142 h per year in math instruction (nearly half of what is spent on Language Arts instruction; Phelps et al., 2012) and only a small portion of formal instructional time is spent learning about science (Falk and Dierking, 2010). Thus, the possibilities and opportunities for learning STEM skills outside of these traditional settings are substantial.

We proposed this Research Topic because despite significant interest in informal learning, particularly in STEM, the research is often disseminated through disparate journals, conferences and other outlets, which do not always share contributors or audiences. This Research Topic is an attempt to aggregate research from multiple fields that share overlapping interests and allow scholars from different fields to share their research in one place. The Research Topic explores unique opportunities to increase participation in STEM activities by sparking children's interest in science, providing meaningful connections to their lives, engaging children and their caregivers, and promoting STEM identities, or the belief that one can participate in STEM, whether inside or outside of the classroom or STEM "pipeline".

The articles in this Research Topic investigate three key issues: (a) investigating how and where informal STEM learning occurs, (2) innovations in the measurement of informal learning, and (3) interventions to increase engagement in and knowledge related to STEM.

Investigating how and where informal STEM learning occurs

How do families and children engage in STEM learning in homes and public spaces? The center of the informal STEM learning ecosystem is the family home. The first group of articles investigate the variations in the kinds of informal STEM activities in which families engage in their homes. Parental beliefs about the importance of STEM is a strong predictor of child outcomes (e.g., STEM careers; Rozek et al., 2017).

Silver et al. investigated the relation between parental beliefs about math (using the Home Numeracy Questionnaire), parent and child gender, and their influence on the frequency of informal math activities with toddlers. Although there were no differences in engagement based on child gender, mothers engaged in more activities than fathers. However, there were no differences in parental engagement when parents had strong beliefs about the value of math. Marcus et al. and Sobel and Stricker investigated family STEM engagement at home. Marcus et al. observed families via Zoom while they participated in a tinkering activity. Half of the families were instructed to create a story about the activity before tinkering whereas the other half were asked to begin the task. Families given the story prompt produced more STEM talk and more detailed reminiscence when compared to the tinkering only group.

Sobel and Stricker investigated the role of parent-child interactions in their children's hand washing behaviors and their causal understanding of germs. Parents and children either watched a handwashing demonstration or jointly participated in a handwashing activity. Children were less likely to use soap when washing their hands when their parents used more directive talk (e.g., setting goals) during the handwashing task, suggesting that providing children with more autonomy during the learning experience increases later engagement. Bae et al. report the results of a 5-year longitudinal study investigating how home science inputs, such as casual talk and science-related materials, influence children's science literacy. Science-related materials in the home were predictive of later science literacy but surprisingly, parent causal talk had a short-term effect and was not predictive of later science literacy. Msall et al. investigated parent attitudes about informal math learning opportunities in the home. A survey of 344 adults with 3- or 4-year-olds measured parent beliefs about what they considered the most effective ways to teach children about math and which approaches they used in their own homes. The results demonstrated a disconnect in that many parents reported using direct instruction but rated incorporating math into daily lives as the most valuable.

Public spaces such as museums and libraries provide unique opportunities for STEM learning. Leech et al. recorded family conversations in a science center and compared the amount of science talk initiated by fathers and mothers. The findings showed that fathers produced more science questions to their children and produced more wh-questions, which promoted more science discourse. Franse et al. report on a project to engage the public in complex social problems, or wicked problems, in science museums. Participants discussed issues in personalized medicine in a focus group and their responses were coded to measure interest in the topic. The findings suggest that exhibits in museums that convey the importance of the issue and build on general interest in science might be most effective in engaging the public in difficult societal questions.

Innovations in the measurement of informal STEM learning

Accurately measuring informal STEM learning presents challenges because of the variation in where and how families engage with STEM content. To better capture children's everyday spatial behaviors (and how those behaviors relate to other aspects of development), Yang et al. developed the Everyday Spatial Questionnaire for Children (EBSQC) for parents to rate children's spatial behaviors. Their research found that the EBSQC significantly correlated with children's sense of direction, adaptive living skills, and cognitive skills.

Douglas et al. and Miller et al. all focused on early math in the home environment. Douglas et al. conducted a series of studies to evaluate measures of parents' knowledge about their children's early math skills—particularly numeracy and patterning. These beliefs likely influence their knowledge about early math and their efforts to support their children's math skills. Miller et al. also sought to evaluate the home environment, particularly for toddlers, using surveys, time diaries, and observations of math talk. They argued that using such diverse methodologies is necessary to measure separate components of the home math environment, including math activities and math talk, which both predict math skills in different ways.

Kominsky et al. and Weisberg et al. also introduced novel methods for measuring children's informal STEM learning–both featuring technology. Kominsky et al. introduced a mobile-based research app called "Talk of the Town" that is designed to capture children's informal STEM learning. "Talk of the Town" will be open-access and facilitate the collection of data from more diverse samples, since data collection will not be constrained by location. Similarly, Weisberg et al. took their research into a non-traditional location—a children's museum—using GoPro cameras. Children wore the GoPro cameras during a 10-min period while they interacted with museum exhibits, family members, and museum staff. Findings suggested the value of interacting with exhibits with caregivers and that children's learning benefitted the most from static (vs.s interactive) exhibits.

Interventions to increase engagement in and knowledge related to STEM

The final group of articles describe interventions to promote learning and engagement through informal STEM activities. Gaias et al. evaluated a library-based program, Fun with Math and Science (FMS), that supports and enhances family STEM interactions. The FMS program includes information about child development, modeling interactions, and allowing families to practice interactions during activities. The results showed that families in the program engaged in more behaviors related to math and science learning than families who did not participate in the program.

Zucker et al. investigated the efficacy of home-based family STEM opportunities delivered virtually. Families were mailed materials to be used during virtual "funshops" in which families watched videos that provided engagement prompts (e.g., wh-questions) and instructions for using materials. The results provide an important caution about virtual delivery and suggest that virtual programming might be limited in its effectiveness because it requires substantial time and resources.

Haden et al. review research on the use of storytelling as a mechanism for enhancing STEM learning and engagement in Latine communities. The review provides evidence that the use of storytelling is a strengths-based approach that leverages funds of knowledge in Latine communities to link STEM learning with everyday activities. Íleri et al. review the evidence regarding how the affordances of toys influence the development of spatial reasoning. They identify toy features, most notably folding, that are most influential for proving interesting and challenging experiences for children. The authors provide recommendations for toy designers that will enhance spatial development through individual play and social interactions.

Makerspaces are popular in many public STEM spaces. Lukowski et al. investigated the impact of structuring makerspaces to include assembly-style making. Although some previous research has suggested that this might reduce creativity and engagement, the results from this study suggest that this approach helped novices feel more comfortable (and less overwhelmed), promoted tinkering, and supported family interactions.

One important facet of informal STEM learning is leveraging everyday experiences to make STEM learning meaningful and interesting. Wang and Walkington created a program in which students shared STEM questions with their peers derived from everyday environments and objects (e.g., Would a cylinder or bag hold more chips?). Students generated more complex questions and deeper explanations compared to more traditional assignments.

This Research Topic encourages reflection by depicting a broad variety of ways in which families engage in informal STEM as well as the wide-ranging contexts in which engagement occurs. It also provides a foundation for future investigations into informal STEM learning by outlining innovations in methodology and intervention. Novel instruments and creative approaches to measurement and data collection allow for better understanding of how informal STEM experiences influence STEM engagement for children and families. Finally, several of the articles provide examples of thoughtful interventions that increase informal STEM learning. By turning a lens on the 95% of children's time spent outside of formal learning contexts, the research within this issue makes a significant contribution toward increasing opportunities for effective STEM learning in everyday situations.

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Informal science, technology, engineering and math learning conditions to increase parent involvement with young children experiencing poverty

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Broadening participation in early science, technology, engineering and math (STEM) learning outside of school is important for families experiencing poverty. We evaluated variations of the Teaching Together STEM pre-kindergarten program for increasing parent involvement in STEM learning. This informal STEM, family engagement program was offered in 20 schools where 92% of students received free/reduced lunch. The core treatment included a series of family education workshops, text messages, and family museum passes. The workshops were delivered at school sites by museum outreach educators. We randomly assigned schools to business-as-usual control or one of three additive treatment groups. Using an additive treatment design, we provided the core program in Treatment A, we added take-home STEM materials in Treatment B, and added materials+parent monetary rewards in Treatment C. The primary outcome was parent involvement in STEM (n=123). There were no significant impacts of any treatment on parent involvement; however, the groups that added take-home materials had larger effect sizes on parent involvement at posttest (ES=−0.08 to 0.18) and later, kindergarten follow-up (ES=−0.01 to 0.34). Adding parent monetary rewards only produced short-term improvements in parent involvement that faded at follow-up. We discuss implications for other community-sponsored family engagement programs focused on informal STEM learning, including considering characteristics of families who were more versus less likely to attend. These null findings suggest that alternatives to in-person family education workshops should be considered when parents are experiencing poverty and have competing demands on their time.

KEYWORDS

parent involvement, informal STEM, pre-kindergarten, family engagement, museum

Introduction

Students experiencing poverty have fewer opportunities for informal science, technology, engineering and math (STEM) during outside of school time (National Research Council, 2009). Although decades of disseminating home literacy research findings has given parents the clear message that reading at home is important, parents are less likely to have clear understanding that early math and science are important home learning activities (LeFevre et al., 2009; McClure et al., 2017). Nationally representative, U.S. datasets show that about 45% of parents read to their young child every day, but only about 12% talk about nature or science daily (Barnett et al., 2020). Yet families can readily support early, informal STEM in already-existing family activities that include STEM, such as cooking, grocery shopping, outdoor play, and games (McClure et al., 2017; Pattison et al., 2020). Decades of empirical evidence shows that parental involvement in learning is related to children's academic achievement (Castro et al., 2015; Ma et al., 2016). Parents are more likely to get involved in their child's learning in preschool than later grades (Welsh et al., 2020), making this an important period for family engagement programs. Yet optimal, effective methods for increasing parent involvement are not well understood. One meta-analysis showed widely-used approaches have little to no effect on long-term outcomes (Grindal et al., 2016). Parent involvement interventions may not be of sufficient intensity for families of lower socio-economic status (Puma et al., 2010) and school-based family education events may be hard for families experiencing poverty to attend (Marti et al., 2018; Barnett et al., 2020).

Therefore, this study examined three variations of a pre-kindergarten (pre-k) program called *Teaching Together (TT) STEM*, designed to increase parent involvement in science and math when delivered at schools where most families were experiencing poverty. The core component was family education workshops, an approach to family engagement that is widely-used in United States schools (National Center for Education Statistics, 2021). But given that workshops may be insufficient to change outcomes (Grindal et al., 2016), we compared this basic treatment to two randomly assigned levels of support that were designed to reduce barriers to parent involvement. Specifically, we added *materials* to a second treatment group with a set of bilingual, take-home STEM activity kits. We added these materials plus *monetary rewards* to a third treatment to reinforce parent involvement. This resulted in three randomly assigned treatment conditions and a control/business-as-usual (BAU) group.

Support for *TT STEM* treatment conditions

The core *Treatment A* sought to increase parents' knowledge and skills to facilitate home-based, informal STEM activities with their preschooler. This included up to six family education workshops hosted at participating schools in the library or cafeteria. At each workshop, bilingual (English/Spanish) outreach educators from a children's museum modeled how to incorporate STEM during every day routines. These afterschools, museum-led workshops used a strengths-based approach that promoted playful, conversation-focused approaches to supporting science and math at home. At the start of workshops, families had pizza and met the museum facilitator. The museum educator explained that STEM is everywhere, showed a video of racially/ethnically diverse parents and children doing STEM, and modeled how to talk to your child about science and math during book reading. Then, families practiced supporting their child's learning at five activity stations while the educator provided support and feedback. The approach focused on talking about science and math during already-existing activities in most families, such as cooking, shopping, and fixing things. At the end of workshops, families received free family admission passes to Children's Museum Houston, as museum spaces uniquely spark early STEM interest (e.g., Haden, 2010). Parents also received a series of text message tips about counting, observing, comparing or other ways to integrate STEM into every day, playful activities. Texts are a low-cost nudge and effective support when they included actionable information for parents to support learning (Caspe and Lopez, 2018; Cabell et al., 2019). All written materials were bilingual and museum educators used a bilingual facilitation in schools serving a majority of bilingual families. These treatments were similar to other culturally-relevant family engagement approaches by using inclusive and strengths-based approaches (Puma et al., 2010), but were offered at schools rather than in other community spaces that may be more welcoming to some families (McWayne et al., 2022). Also, the treatments did not feature adaptations specific to racial/ethnic cultures (*cf.* Leyva et al., 2022).

The second *Treatment B* added nine take-home STEM kits because families experiencing poverty may have limited access to STEM-related materials and informational children's books to facilitate learning (Reinhart et al., 2016; Neuman, 2017). Effective programs for supporting STEM knowledge often include family activity kits to support STEM inquiry at home (Clements and Sarama, 2008; Kaderavek et al., 2020). Meta-analytic reports conclude that both increasing parent involvement in learning and providing age-appropriate home learning materials are linked to children's academic outcomes (Boonk et al., 2018). Increasing home learning resources may be particularly important for students who begin pre-k with limited math skills (Powell et al., 2012). *TT STEM* take-home STEM activity kits included inquiry-based activities with step-by-step photos, bilingual instructions, and aligned informational tradebooks.

The third *Treatment C* added rewards to motivate parents. It is possible that some parents require more than just information and materials to overcome negative cultural stereotypes or past experiences with science or math (McClure et al., 2017). Therefore, the third treatment added parent rewards of $2.50 per STEM activity completed. These extrinsic, monetary incentives were designed to demonstrate the value of doing STEM with your child while also offsetting potential perceived costs, such as effort demands or lost time for alternative activities (Parker et al., 2017). Other experimental studies with parents of preschoolers show rewards of $0.50 for completing book reading sessions effectively increase parent involvement (Justice et al., 2018). Although the argument against monetary rewards in parenting programs is that they are unlikely to feasible in practice when offering no-cost family engagement programs, some experimental evidence shows monetary incentives increase the proportions of low-income families that complete parenting interventions (e.g., Heinrichs, 2006). Yet, other experiments show limited value of monetary incentives (Dumas et al., 2010). Thus, this variable warrants further study.

Study purpose

Our primary goal was to understand what components could be added to an informal STEM family engagement program to best improve parent involvement. The museum educators in this study previously developed the family education workshops with bilingual (Spanish/English) families experiencing poverty (Garibay, 2007). The position of the museum facilitators was as a community partner that sought to broaden access to informal STEM learning for children experiencing poverty. The museum worked with researchers to evaluate two research questions (RQ) about the basic, core family engagement program and two additive conditions theorized to increase parent involvement.

> RQ1: To what extent did families attend the core treatment activity of *TT STEM* workshops and did participation vary by background characteristics?
>
> RQ2: Which conditions better increased parent involvement in STEM activities with their child?

We hoped for >75% attendance at workshops, but past *Teaching Together* studies with families experiencing poverty showed an average of 25% attendance (Zucker et al., 2021). We hypothesized that parents in all treatment conditions would report increased involvement in STEM, but that parents who received the take-home kits would report more frequent STEM because providing materials reduced barriers. We expected adding contingent monetary rewards would further boost parent involvement because it reinforced the value of doing STEM.

Method and materials

This study occurred in the 2019–2020 school year in a south-central U.S. state within 20 schools where 92% of students received free/reduced lunch. We used a cluster randomized control trial design, randomly assigning conditions at the school level to: BAU control, Treatment A/Core, Treatment B/Add Materials, and Treatment C/Add Incentives. All pre-k families in participating schools were invited and written consent was required (IRB # HMC-MS-15-0759). The study was advertised using flyers in school-home communication folders or parent meetings hosted at the school. Amongst consented families, we randomly selected an average of four parent–child dyads per classroom (SD = 2.32), totaling 181 parent–child dyads. Due to 17 families completing the pretest survey after treatment started and attrition at posttest, 123 families represent the final sample. Table 1 shows demographics. Mean child age was 4 years and 5 months (SD = 0.34 months; range 3 years, 5 months to 5 years, 0 months); 51% were female. Most participants were Black or Hispanic/Latine. About 50% of families spoke a language other than English at home ($n = 88$, 63% Spanish). Median yearly household income was $20,001–$30,000. Families received $50 for completing assessments in Fall/baseline, $50 for Summer/posttest, and $20 in Winter/follow-up. Testing occurred September–November 2019 for pre-k baseline, May–July 2020 for pre-k posttest and January–March 2021 for kindergarten (K) follow-up. Detailed participant demographics, attrition analysis, and CONSORT flowchart are in Online Supplementary materials SM1, SM2. Treatment activities were explained above, but sample materials and cost analysis are in Online Supplementary materials SM3–SM7. Parents reported high satisfaction with workshops ($M = 3.84$, SD = 0.47) on a 4-point scale at workshop exit surveys. Families in the control group experienced their school's BAU family engagement offerings and a set of developmental text messages from the researchers to maintain contact/reduce attrition; this is detailed in Online Supplementary material SSM8.

TABLE 1 Demographic characteristics ($n = 123$).

	C ($n = 37$)	TxA ($n = 15$)	TxB ($n = 37$)	TxC ($n = 34$)
Child female?	0.59	0.33	0.54	0.56
	(0.50)	(0.49)	(0.51)	(0.50)
Other language at home?	0.30	0.53	0.68	0.71
	(0.46)	(0.52)	(0.47)	(0.46)
Mother's level of education	4.51	4.53	4.54	4.82
	(1.73)	(1.55)	(2.05)	(1.47)
Father's level of education	3.46	4.93	3.69	4.34
	(1.24)	(1.94)	(2.00)	(2.13)
Is caregiver Hispanic?	0.25	0.40	0.47	0.45
	(0.44)	(0.51)	(0.51)	(0.51)
Caregiver race				
Black	0.70	0.47	0.49	0.29
	(0.46)	(0.52)	(0.51)	(0.46)
White	0.08	0.33	0.32	0.38
	(0.28)	(0.49)	(0.47)	(0.49)
Household income	3.35	4.36	3.63	3.59
	(1.81)	(1.21)	(1.59)	(1.91)

C, Control; TxA, Core program; TxB, Add kits; TxC = Add rewards.

Measures

The primary outcome was a 10-item parent involvement survey collected at baseline, pre-k posttest, and kindergarten follow-up. Responses ranged from: *1*-Not at all; *2*-Once or twice a week; *3*-Three or more times a week, but not everyday; to *4*-Everyday. Items asked "How many times in the past week have you…" around STEM activities such as "compared sizes of objects or toys with your child?" "talked to your child about plants, animals or other living things?" These items were adapted from the Head Start Family and Child Experiences Survey (West et al., 2007). Sample reliability was Cronbach's $\alpha = 0.85$. Online Supplementary Table SM9 shows descriptives and all items in the parent involvement survey.

Data analysis plan

To answer RQ1, we used descriptive statistics to group families into groups of non-attenders, lower, and higher attenders. We then explored the statistical significance of these levels using the Kruskal-Wallis test, a non-parametric one-way ANOVA.

To examine RQ2, we first estimated the intent-to-treat (ITT) using ordinary least squares regressions, correcting for clustering using robust standard errors at the classroom and school-level. Model 1 regressed the outcome on the baseline and three treatments (control as reference). Model 2 added family-level demographic characteristics: child's sex (male = 0; female = 1); language other than English at home (0 = no; 1 = yes); highest level parent education; number of parents in a STEM-related career (0 = none; 1 = one parent, 2 = two parents); race/ethnicity of parent with three dummy variables for White, Black, and Hispanic. For Model 3, we added school-level variables from the Texas Education Agency 2019–2020 school profile reports: percent economically disadvantaged students, percent Limited English Proficiency students, and percent special education students. We also report treatment-on-treated (TOT) estimates by dividing the ITT estimates by the percent of treatment group members who were treated, defined as attending at least one workshop. This adjustment is appropriate given there were no cross-overs in our experiment (only no-shows). We had minimum levels of missing data on family-level covariates in Models 1 and 2. We used a multiple imputation approach to missing data.

Results

RQ1-attendance patterns

Across all groups, we had rather low, average 25% attendance rates ($M = 1.5$ workshops, SD = 1.7, range = 16–36%). Rates were 40% for Treatment A, 65% for Treatment B, and 56% for Treatment C. Parents reported the most salient barriers to attendance were limited time due to competing work/family priorities (Supplementary Table SM10). The pattern of attendance, shown in Online Supplementary Figure SM2, shows parent attendance improved at workshops 2 through 4 but, at workshops 5 and 6, attendance was lower. Descriptively, we looked at characteristics of families most likely to attend the workshops. To this end, we categorized attendance into five groups: *Group 0* had families who attended no STEM workshops ($n = 60$); *Group 1* families attended <= 25% ($n = 22$); *Group 2* families attended between > 25% and < = 50% ($n = 24$); *Group 3* families attended > 50% and < = 75% ($n = 16$); *Group 4* families attended > 75% of offered workshops ($n = 15$). Table 2 reports background characteristics by descriptive group. Families that attended > 50% of workshops had higher levels of mother's education and father's education, higher proportion of White parents, and higher incomes than those families who attended less than half. The only significant characteristic at $p < 0.05$ was father's education ($p = 0.034$). In the lower panel of Table 2, we connect these varying attendance rates to fixed costs of delivering workshops. This shows how the cost per school increases when fewer families attend due to largely fixed costs.

RQ2-conditions best increasing parent involvement

Table 3 presents three model specifications described above for ITT and TOT. There were no statistically significant associations, thus we interpret models based on effect sizes of TOT. The most robust Model 3, which adjusts for both family and school characteristics before comparing treatments to control, found at pre-k posttest that Treatment A and B produced no meaningful differences in parent involvement (TxA ES = −0.01; TxB ES = −0.08). But Treatment C higher pre-k posttest parent involvement compared to control (ES = 0.18).

The results for the delayed, follow-up K outcomes (lower panel Table 3) were, again, non-significant but the pattern of ES differed from pre-k posttest. For Model 3, Treatment A had substantially lower levels than control (ES = −0.94), Treatment B was higher than control (ES = 0.34), and Treatment C was similar to control (ES = −0.01). Parent surveys indicated the most salient barriers to parent involvement in STEM were limited time, limited materials/resources, and knowledge of how to support early STEM (Supplementary Table SM10).

Discussion

This study explored informal learning conditions that are most likely to increase parent involvement in STEM with their young child. We randomly assigned schools to a control condition or one of three additive treatment groups with museum-led STEM workshops within school facilities as the core component. We added take-home activity kits and parent rewards in the other treatments. There were no significant impacts of any treatment on

TABLE 2 Workshop attendance.

Background characteristics	Group 0: 0% (n = 60)	Group 1: ≤25% (n = 22)	Group 2: ≤50% (n = 24)	Group 3: ≤75% (n = 16)	Group 4: >75% (n = 15)	Kruskal–Wallis test
Mother's highest education	4.43 (1.63)	4.67 (1.62)	3.88 (1.62)	4.86 (1.92)	4.73 (2.05)	$\chi^2(df = 4) = 5.14$, $p = 0.273$
Father's highest education*	4.15 (1.76)	4.20 (1.77)	3.17 (1.61)	4.71 (2.70)	5.29 (2.40)	$\chi^2 (df = 4) = 10.39$, $p = 0.034$*
Mother STEM related	0.33 (0.48)	0.35 (0.49)	0.26 (0.45)	0.50 (0.52)	0.13 (0.35)	$\chi^2 (df = 4) = 4.96$, $p = 0.291$
Father STEM related	0.39 (0.49)	0.29 (0.47)	0.45 (0.51)	0.64 (0.50)	0.36 (0.50)	$\chi^2(df = 4) = 4.42$, $p = 0.352$
Home language other than English	0.48 (0.50)	0.43 (0.51)	0.71 (0.46)	0.60 (0.51)	0.73 (0.46)	$\chi^2 (df = 4) = 6.88$, $p = 0.143$
Hispanic caregiver	0.33 (0.48)	0.30 (0.47)	0.48 (0.51)	0.53 (0.52)	0.40 (0.51)	$\chi^2 (df = 4) = 3.48$, $p = 0.481$
Race caregiver						
Black	0.55 (0.50)	0.57 (0.51)	0.29 (0.46)	0.40 (0.51)	0.33 (0.49)	$\chi^2 (df = 4) = 6.85$, $p = 0.144$
White[+]	0.21 (0.41)	0.24 (0.44)	0.38 (0.49)	0.47 (0.52)	0.53 (0.52)	$\chi^2 (df = 4) = 9.04$, $p = 0.060$
Household Income	3.46 (1.88)	3.28 (1.45)	3.24 (1.81)	4.08 (2.10)	3.92 (1.44)	$\chi^2 (df = 4) = 2.58$, $p = 0.631$
Treatments (Tx)						
TxA	0.32 (0.47)	0.27 (0.46)	0.29 (0.46)	0.13 (0.34)	0.13 (0.35)	$\chi^2 (df = 4) = 3.85$, $p = 0.427$
TxB	0.35 (0.48)	0.50 (0.51)	0.29 (0.46)	0.50 (0.52)	0.67 (0.49)	$\chi^2 (df = 4) = 7.53$, $p = 0.110$
TxC	0.33 (0.48)	0.23 (0.43)	0.42 (0.50)	0.38 (0.50)	0.20 (0.41)	$\chi^2 (df = 4) = 3.13$, $p = 0.536$
Cost Analysis (if *n* families attend)	*n* = 0	*n* = 6	*n* = 11	*n* = 17	*n* = 22	
Workshop fixed costs per school[a]	$1,879.87	$341.79	$170.90	$113.93	$85.45	

[+]$p < 0.10$; *$p < 0.05$; **$p < 0.01$; and ***$p < 0.001$.
[a]This does not include the variable cost of family museum passes valued at up to $84; this is the only variable treatment A/core costs, as all other costs are fixed.

TABLE 3 Parent involvement models comparing treatment (Tx) groups to control.

	Model 1					Model 2					Model 3				
	ITT	Robust standard error	Value of *p*	TOT	Effect size for TOT	ITT	Robust standard error	Value of *p*	TOT	Effect size for TOT	ITT	Robust standard error	Value of *p*	TOT	Effect size for TOT
Posttest, *n* = 123															
TxA	−0.15	0.18	0.419	−0.36	−0.57	−0.09	0.17	0.594	−0.23	−0.36	0.00	0.17	0.989	−0.01	−0.01
TxB	−0.25	0.15	0.095[+]	−0.39	−0.61	−0.19	0.15	0.229	−0.29	−0.46	−0.03	0.13	0.802	−0.05	−0.08
TxC	−0.16	0.11	0.161	−0.29	−0.46	−0.07	0.11	0.529	−0.13	−0.20	0.07	0.12	0.583	0.12	0.18
Follow-up, *n* = 74															
TxA	−0.29	0.15	0.063[+]	−0.63	−0.94	−0.09	0.17	0.586	−0.20	−0.30	−0.29	0.18	0.108	−0.63	−0.94
TxB	−0.15	0.21	0.484	−0.24	−0.36	−0.05	0.23	0.830	−0.08	−0.12	0.14	0.19	0.478	0.23	0.34
TxC	−0.07	0.16	0.678	−0.10	−0.15	0.00	0.20	0.986	0.01	0.01	0.00	0.18	0.987	0.00	−0.01

ITT, intent-to-treat; TOT, treatment-on-the-treated. [+]$p < 0.10$; *$p < 0.05$; **$p < 0.01$; and ***$p < 0.001$.

the primary outcome of parent involvement in STEM. Treatment A/Core program showed no difference at pre-k posttest but the largest and negative difference at K follow-up. Treatment B/Add Materials showed no difference at posttest but a moderate, non-significant positive difference at follow-up. Treatment C/Add Incentives showed a small positive difference at posttest, but no difference at follow-up. In other words, Treatment C's monetary rewards for parents showed promise for short-term outcomes, but benefits faded over time. We consider potential explanations for the larger effect sizes of Treatments B and C that added materials to support STEM learning at home. These treatment findings and attendance patterns have implications for broader family engagement approaches.

Parent involvement is linked to children's academic achievement (Castro et al., 2015; Ma et al., 2016). Although we found no significant effects of the *TT STEM* program, proving take-home family kits produced larger effect sizes. This is similar to prior reports that providing pre-k families experiencing poverty with access to typical family engagement programs may not be sufficient (Puma et al., 2010; Grindal et al., 2016). Like other studies that provide pre-k families with treatment packages that include home materials and others supports (Clements and Sarama, 2008; Welsh et al., 2020), this study found that families benefited most from conditions that included the take-home STEM kits. The contribution of this study is that we unbundled treatment packages to understand added benefits of different components. Interestingly, adding rewards in Treatment C improved immediate parent involvement (ES = 0.18), but these benefits faded by kindergarten follow-up when only Treatment B with take-home kits showed sustained improvement in parent involvement (ES = 0.34). Because all activity kits were delivered at the outset of the intervention, it is possible that providing kits allowed parents to build more culturally-relevant engagement strategies in their home than Treatment A that used a more traditional school-to-home approach of attending workshops to increase parent involvement (*cf.* McWayne et al., 2022).

Provision of STEM learning materials to families experiencing poverty warrants future consideration. We expect that providing materials alone, without education workshops and resources, will be ineffective (e.g., Neuman, 2017). Yet the lack of significant differences may be due to several factors. The limited scope of the program may not have developed broad and deep interest in informal STEM over multiple stages of development (National Research Council, 2009). Indeed, some effective STEM approaches using take-home materials span several grade levels (Kaderavek et al., 2020) or ensure many museum visits (Pattison et al., 2020). Yet other, intensive parent coaching studies that intervene in pre-k and kindergarten find sustained effects on parent involvement through Grade 5 (ES = 0.24; Welsh et al., 2020). Future studies should tease apart issues of intensity of parent involvement supports needed across grades as well as the extent to which step-by-step kits versus more open-ended materials for STEM exploration are beneficial over time.

The finding that the benefits of the added monetary rewards condition faded when they were withdrawn at the kindergarten follow-up survey, aligns with theories that performance-based extrinsic rewards have proximal influences on behaviors adults already hoped and intended to do (Parker et al., 2017). For example, the rewards may have urged parents to overcome immediate time pressures supporting STEM learning; parents noted limited time was their primary barrier to involvement in STEM. This aligns with a recent pre-k shared book reading study that found the most effective short-term technique for encouraging parents to read with their child was paying parents $0.50 for each book reading session (Justice et al., 2018). Justice and colleagues concluded that rewards can support parent involvement particularly when time pressures are a salient barrier.

Although parents reported high satisfaction with the *TT STEM* workshops, they only attended an average of 25% of offered workshops. It is possible that these satisfaction data are overestimated because, out of respect for perceived museum experts, parents reported that the events were engaging and useful; this is common when families perceive a hierarchical relationship (McWayne et al., 2022). Other family engagement studies show families complete 35–75% of offered activities (Justice et al., 2018; Kim et al., 2019; Welsh et al., 2020). We found significantly higher workshop attendance for families with higher paternal education levels and trends for higher income and White families attending more events. These findings are troubling in that the families experiencing poverty and racial/ethnic minorities were the target populations for our goal of broadening access to early STEM opportunities (National Research Council, 2009). This could suggest the *TT STEM* program was not sufficiently tailored to the needs of these populations. Alternatively, there may be an upper limit to the number of workshops in-person parents can attend. In future studies, we will consider flexible or adaptive options to improve uptake (*cf.* Kim et al., 2019). Our cost analysis findings are noteworthy because they show how the fixed costs of family education workshops move from costs per student from $85 if all families in a classroom attend to $342 if only 25% attend. This has implications for other family engagement programs to consider how to schedule and market events to ensure high attendance (Beckett et al., 2009).

Limitations

There are shortcomings of this study to note. First, we did not measure child outcomes. Second, this sample likely was underpowered to detect potentially meaningful effects. Third, a small number of workshops were cancelled due to local emergencies or the start of the COVID-19 pandemic. The pandemic could have impacted the reliability of our parent involvement survey. Finally, there was greater attrition than desired including low response rates on the kindergarten parent surveys. These limitations limit the conclusions we can draw from these data.

Conclusion

These patterns of findings for parent involvement align with meta-analyses that light touch educational workshops produce null to small impacts (Grindal et al., 2016). Yet the results demonstrate that families experiencing poverty can be better supported to engage in early STEM activities with their young children under certain conditions. That is, consistent with past research (Boonk et al., 2018), giving families access to educational resources alongside materials that scaffold informal learning were the most beneficial treatments for improving parent involvement in this sample. This is important for other programs with goals of promoting broad access to informal learning in ways that ensure access to families experiencing poverty.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Committee for the Protection of Human Subjects (CPHS) at University of Texas Health Science at Houston, Medical School (MS). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin. Written informed consent was obtained from the individual(s) for the publication of any identifiable images or data included in this article.

Author contributions

TZ: conceptualization, qualitative analysis, resources, writing original draft, writing—reviewing and editing, visualization, supervision, and funding acquisition. GM: conceptualization, quantitative analysis, writing original draft, writing—reviewing and editing, visualization, and data curation. MA: conceptualization, supervision, and writing—reviewing and editing. CM: supervision, writing reviewing and editing, funding acquisition, and project administration. CE: supervision, writing—reviewing and editing, and project administration. JS and LL: data curation, visualization, and cost analysis. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Parent–child interaction during a home STEM activity and children's handwashing behaviors

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We examined correlations between a home-based STEM activity illustrating the importance of soap use during handwashing and children's (4-to 7-year-olds, $N=81$, 42 girls, 39 boys) use of soap when washing their hands. Parents and children either participated in or watched the activity. Children reflected on the activity immediately afterward and a week later. Parent–child interaction during participation related to the frequency of unprompted soap use during handwashing, controlling for performance on other, related cognitive measures. Children whose parents were more goal-directed, and set goals for the interaction, were less likely to use soap spontaneously when handwashing in the subsequent week. The amount of causal knowledge children generated when they reflected on the experience immediately afterward also influenced whether children used soap when washing their hands. Reducing the autonomy children believe they have during a STEM-based activity potentially leads them to not engage in a behavior related to the activity on their own. Overall, these data suggest that parent–child interaction during STEM activities can influence the ways children encode and engage with those activities in their everyday lives. Given that the ways children wash their hands might mitigate the spread of disease, interventions that focus on providing children with the belief that STEM activities are for them might be broadly beneficial to society.

KEYWORDS
parent–child interaction, handwashing, prevention of disease transmission, STEM engagement, goal setting

Introduction

Collaborative, playful interaction is an essential part of young children's learning experience (e.g., Weisberg et al., 2014). Hands-on informal learning environments, like museums, offer rich ecosystems for studying these kinds of interactions, allowing researchers to capture children's play, STEM exploration, and parent–child engagement in a naturalistic way (e.g., Allen, 2004; van Schijndel et al., 2010; Callanan, 2012; Sobel and Jipson, 2016; Falk and Dierking, 2018). But informal learning happens in many contexts (e.g., Ridge et al., 2015; Hassinger-Das et al., 2018, 2020; Gaudreau et al., 2021; Morris et al., 2021), and most critically in the home. Our goal is to examine the translation of parent–child interaction practices in hands-on museum settings to similar hands-on STEM-based activities in the home to consider whether there are corresponding learning outcomes from those interactions.

Parent–child interaction has been studied in the home in many ways, particularly through observational means (Parker et al., 1999; Aspland and Gardner, 2003; Raikes et al., 2006; Deak et al., 2014). Parents support children's learning through various facets of their cognition and language (e.g., Tamis-LeMonda et al., 2001, 2004; Song et al., 2014). Our goal is to build upon this observational work and use our findings to contribute to museums' practices for engaging families outside their physical space. To do this, we presented families with a STEM-based activity, developed in conjunction with museum educators, to be done in the home. We then examined parent–child interaction during this activity, following other investigations of parent–child interaction in museum settings, and then measured children's subsequent reflection about the activity and their engagement with real-world behaviors as it relates to the activity.

Because of its relevance to the COVID-19 pandemic (and to mitigating the spread of disease in general), we have chosen children's handwashing as the behavior of interest, and particularly, their use of soap during handwashing to prevent germ transmission. For older children (6^{th} graders), studies have shown that the way in which parents wash their hands, and the nature of the bond between parents and children, relates to children's own handwashing behavior (Song et al., 2013). Children's beliefs about germs, how germs spread, and how to mitigate this spread is not only relevant to promoting good hygiene, but also preventing the spread of infectious diseases (Au et al., 1999, 2008). Observational studies of children's handwashing have shown that 3-to 6-year-olds wash their hands before eating, after outdoor play and after bathroom use only 15–48% of the time in daycare settings (van Beeck et al., 2016, see also Toyama, 2016a). Educating young children on the importance of soap use during handwashing reduces the physical number of bacteria on their hands (Kim et al., 2012; Utario et al., 2018). Educating young children on germs and handwashing also increases their understanding of the relation between germs and disease prevention (e.g., Toyama, 2016b; Crosby et al., 2019; Jess and Dozier, 2020; Younie et al., 2020 for a review). This literature, however, does not highlight any case in which the interaction between parents (or teachers) and children influenced children's subsequent handwashing behavior.

Our question was whether presenting families with an activity that highlights what soap does during handwashing affects children's handwashing behaviors, compared with watching that activity on video. Subsequently, we also considered whether the ways in which parents and children interact during this activity relates to children's use of soap during subsequent handwashing. To this end, we first highlight studies on digital learning and its similarities and differences to hands-on demonstrative learning. We then consider how parent–child interaction during hands-on activities might affect children's learning and engagement.

STEM learning from digital media

Digital educational resources, which include online games, websites, apps, and videos, are thought to serve as an effective way to engage children in STEM learning—both in and out of the classroom. In the home, parents often use these kinds of media as a supplemental tool to reinforce kid-friendly math and science concepts; the use of internet videos, in particular, is a way to visually aid children's science inquiry and encourage scientific curiosity (Hightower et al., 2019). In elementary schools, teachers see digital-based resources as a way to reenergize the classroom curriculum; providing real-world relevance and a different, more unconventional way of reaching students (Hanson and Carlson, 2005). From videos, young learners are able to experience concrete, visual examples of the content being explored (Nugroho and Muhtadi, 2020). Video learning also positively impacts children's performance, participation, and interest in scientific topics (e.g., Giannakos et al., 2015; Palaigeorgiou and Papadopoulou, 2019; Chen et al., 2021). As such, it is possible that watching videos of the same STEM demonstrations affords children the same learning opportunities as participating in those demonstrations themselves. In our study, we contrasted dyads who participated in the STEM demonstration with those who watched that demonstration for the purpose of comparing these groups.

Hands-on STEM learning and parent–child interaction

For decades, however, hands-on museums and science centers have focused on providing the public with exploratory and participatory STEM learning experiences. The rationale for this pedagogy, led by Oppenheimer (1968), is that verbal explanation of science concepts alone is not enough to initiate understanding. Hands-on STEM activities engage visitors with real objects and phenomena and encourage active participation through autonomy, initiative and choice (Caulton, 2006). For children, opportunities to explore museum exhibits through hands-on manipulation increases their time spent engaging with STEM content (Crowley et al., 2001a; Knutson et al., 2016; Willard et al., 2019). For example, families' interaction with a natural history museum's diorama increased significantly after the implementation of a range of hands-on interventions. One of the most successful interventions was "Objects and Tools" which featured real-life specimens and investigative tools (deer antlers, jaw bones, measuring tools, etc.) that families could explore freely in tandem with the diorama (Knutson et al., 2016). Additionally, hands-on objects can increase joint talk between parents and children and encourage children's experience recall after their visit (Jant et al., 2014). These benefits of hands-on exploration are made even stronger when the experience is a collaborative one, with scaffolded support from an adult (e.g., Crowley et al., 2001a; Van Schijndel et al., 2010; Jant et al., 2014; Legare et al., 2017; Willard et al., 2019).

In particular, the ways in which parent–child interaction scaffolds children's STEM learning and engagement has been studied in three ways. First, how children and parents talk to each other during the activity affords meaning construction and the transmission of causal knowledge (e.g., Callanan and Jipson, 2001; Leinhardt and Knutson, 2004; Eberbach and Crowley, 2017). For example, elaborative talk about science in informal settings, such as parents generating explanations and asking open-ended questions, relates to children's engagement with exhibits and to their ability to remember more about their experience (e.g., Benjamin et al., 2010; Jant et al., 2014). The explanations parents generate provide a structure for the activities that children engage in, which may help children better understand the information inherent in the exhibit (e.g., Crowley et al., 2001b; Tare et al., 2011; Callanan et al., 2020; Chandler-Campbell et al., 2020, although see Joy et al., 2021, for a different perspective).

For example, in a children's museum tinkering space, the more parents generated STEM-based talk while engaging in a tinkering activity with children, the more likely children were to talk about STEM-related content when asked to reflect on the activity (Acosta et al., 2021). Similarly, encouraging parents to promote spatial talk with their preschoolers led to preschoolers generating more spatial language during their play, and the extent to which children generated such language related to their spatial problem solving on their own (Polinsky et al., 2017). Generally construed, the more science talk parents generate when exploring an exhibit (in this case, discovering the identity of a novel object), the more engaged children were by the activity (Valle and Callanan, 2006; Haden, 2010; Callanan et al., 2017), and the more personal connections parents make for children during their conversations at exhibits, the longer children spend exploring the exhibit (e.g., Crowley et al., 2001a; Pattison et al., 2018).

Second, how parents set goals or allow children to set goals during play relates to children's engagement with the interaction they have with their parents. For example, Sobel et al. (2021) showed that parents who were more directive in setting goals during free play at a circuit exhibit had children (specifically 4-to 7-year-olds) who participated in fewer circuit building challenges, controlling for age and how well children performed at building circuits. Similarly, Leonard et al. (2021) similarly found that when adults "take over" their interaction with children during a challenging task – i.e., when adults engage in the task for the child – those children were rated as persisting less on a measure of global persistence. These researchers also found that children engaged with stimuli for less time on their own when an adult experimenter took over the interaction than when the adult engaged in other activities (see also Medina and Sobel, 2020, for similar findings when children engage in a learning activity with a caregiver).

An interpretation of these studies is that when parents reduce children's autonomy during interaction, children become less engaged with the activity and are less likely to internalize and encode their participation. Such a possibility has support in the adult social psychological literature, as well as in parent–child interactions among older children. Deci and Ryan (2000), for instance, suggest that the extent to which adults feel they have autonomy in their actions – that they can "self-organize experience …and to have activity be concordant with one's integrated sense of self" (p. 231) – the more they engage in healthy development and experience well-being. Applying this hypothesis to children, Grolnick & Ryan, 1987 found that when adults placed fifth-graders in a directed learning environment that controlled what children were allowed to do (by indicating that their participation was a test and that they should work hard), their motivation for learning was reduced, compared with a case in which less controlling and evaluative language was used. In formal academic settings, the extent to which parents supported their 3rd to 6th graders' autonomy positively correlated with children's self-regulatory behaviors and academic achievement (Grolnick & Ryan, 1989). While we build on more recent studies of younger children's interaction with parents during informal learning activities, the negative influence of "taking over" behaviors or of parents' goal directedness has its basis in the rubric of the social psychology of self-determination.[1]

Third, how children reflect on informal learning experiences with their parents after the fact indicates what they understand about the experience (e.g., Haden, 2010). For example, if causal information is presented to children during their interaction with parents in a museum setting, children talk more about that causal knowledge when they reflect on the experience even 2 weeks later (Marcus et al., 2017). Reflection also promotes consolidation, which can be applied to subsequent activities. Marcus et al. (2021) showed that having parents and children reflect on their play at a museum exhibit together related to children's understanding of the engineering knowledge inherent in the exhibit when children were tested in the home a week later. This suggests that parent–child interaction and the ways in which children reflect on the experience in the museum not only transfers to the home environment, but also that reflection on such experiences relates to how children are motivated to engage in tasks and problem-solve more generally. The more causal knowledge children might have, the more likely they might be to internalize and apply their experiences during parent–child interaction to other facets of their lives.

1 An important point about self-determination theory (Deci and Ryan, 1985, 2000) is that it posits that such motivation stems from a set of innate psychological needs, which are not particularly based in physiological drives. While this is certainly a possible explanation, we are agnostic to this specific aspect of this account.

The present study

In the present study, we asked parents and children to engage in a structured activity. The activity we used centered around demonstrating the effect that soap has on particles in water. Of importance is whether children encode the difference between using and not using soap during their experience, as well as whether parents set goals for their children's participation in the activity, thus increasing or decreasing children's perceived autonomy. Our specific hypothesis was that parents who engaged in more goal-setting behaviors would have children who showed reduced engagement with what could be learned from the measure. To provide a baseline, we also had a separate group of parents and children watch the activity on a video, so that children were exposed to the content of the activity, but without the possibility of controlling their behavior during participation.

Conversations between parents and children were recorded during and immediately after their participation in the activity or their watching of the demonstration video. Children were also asked to reflect on their experience with the demonstration in the same session and approximately 1 week later in a separate session. Additionally, in both sessions, children were given a set of measures to control for their general cognition and to assess their understanding of disease transmission. This ensured that any difference we potentially observed between conditions related to the conditions and not children's existing causal knowledge or cognitive capacities. During the time between the two sessions, parents were sent a daily Google Form, in which they were asked to reflect on one observation of their children's handwashing behaviors that day – particularly whether they washed their hands before eating or after bathroom use and whether they used soap. Summary statistics from these reports will constitute our dependent measure, and we will consider whether facets of parent–child interaction, children's reflection, and their knowledge of disease transmission influence this handwashing behavior.

For the at-home STEM activity, we chose a demonstration in which grains of black pepper are placed in a bowl of water, and displaced when soap (particularly soap on a finger) is put into the bowl. Children either observed a video of the demonstration or physically participated in it, and through this experience, were able to see what happened when they or another person dipped their finger into the bowl without, and then with the soap. Without soap, the pepper sticks to the person's finger. With soap, the pepper moves away from the person's finger, as if repelled. Of course, this is not the actual causal mechanism – the soap does not repel the pepper; rather, the soap breaks the surface tension of the water because one end of the soap molecule is hydrophobic. However, the goal of this demonstration is not to teach children about surface tension.[2] Rather, the goal is to present children with a scenario in which using soap affects how they might visualize and represent germs sticking to their body, a fact that even the youngest children of this age can denote through symbolic representation (e.g., DeLoache, 1987). Critically, the movement of the pepper is fast and surprising, creating an engaging result, which is easily perceptually accessible.

As such, there are three research questions we wish to address. First, does the way parents and children interact during their participation in the activity relate to children's subsequent handwashing behaviors? We look at this in two ways: by considering whether there is a difference between dyads who actually participated in the activity and those who watched a video of the activity and by examining whether parental goal setting during the activity mediated handwashing behavior in the former group. Of interest was whether any hands-on participation would facilitate children's handwashing behavior or if they specifically needed the activity to be non-parent-directed. This question also motivated an important facet of our investigation, which was that at no point during the demonstration or participation did we tell parents or children that the study was about children's handwashing. We did not want to bias parents from talking about handwashing, germs, or disease prevention; rather, we wanted to see if this talk would emerge naturally. Moreover, we did not want to bias parents from enforcing handwashing or soap use after the demonstration; we similarly wanted to see whether children would engage in more handwashing or soap use on their own.

Second, does the conversation children have with their parent during the activity or their reflection on their experience with the activity relate to their handwashing behaviors? To answer this question, we focus on the causal language generated by parents and children during their participation or viewing of the activity as well as the causal language children generate during their reflections. Of particular interest here is whether the generation of causal language by parents or children, particularly about germs, handwashing, or disease transmission, during the activity related to children's subsequent handwashing. Again, because our goal was to examine everyday parent–child interaction, we did not explicitly tell parents that the goal of the investigation was to study handwashing or soap use. This question, however, considers the extent to which parents or children's spontaneous application of this knowledge to the situation influenced children's subsequent behavior.

Third, are there individual differences in children's knowledge of disease transmission, or other facets of their cognition that might moderate their handwashing behavior? Here, we consider how children respond to specific questions designed to assess their knowledge of disease transmission in general as well as broader measures of cognitive development, such as working memory and theory of mind. These measures were chosen both as measures of general cognitive development, but also because greater memory or social-cognitive capacities might moderate how one learns from parent–child interaction. The expectation was that any relations we found of interest to the research questions described above would not be due to general cognitive development, and thus unrelated to performance on the theory of mind and working memory measures.

2 Whether this demonstration can be used for that purpose is beyond the scope of this investigation.

Materials and Methods

Participants

The final sample included 81 children between the ages of 49 to 96 months (42 girls, 39 boys, $M_{age} = 72.45$ months, SD = 13.69 months). This sample size was determined by a power analysis based on comparison between the two conditions, assuming a large effect ($f = 0.35$), and $\alpha = 0.05$ and $\beta = 0.80$. Participants were recruited from a database of families who had previously participated in studies in the laboratory or children's museum in Location Blinded for Review as well as through an advertisement on Childrenhelpingscience.org.

Children were tested over two sessions, both conducted over Zoom. In the first session, they participated in or observed the demonstration with their parent (74 with female parent, 7 with male parent), and then tested on their own. In the second session, approximately 1–2 weeks later, children were tested by themselves (after their parent established the Zoom call). Parents were invited to stay in the room while their child was tested individually, but instructed not to prompt them to respond, or respond for them. Three additional dyads were tested, but not included in the final sample. Two only participated in the first session; the third was uncooperative and did not provide a complete dataset. Participating families were compensated $20 for each session ($40 total).

We collected demographic information from participating parents *via* a self-report questionnaire which asked for parent age, household income, household language, parent education level, and family race/ethnicity information. Parents were told to provide as much information as they were comfortable sharing. All parents provided some demographic information. Seventy-two (89% of the sample) reported that their children came from monolingual English-speaking homes. Nine (11%) reported their children came from bilingual homes – always English and another language (Spanish, Portuguese, French, German, Arabic, and Tamil were represented).

Using open-ended questions, we asked parents to describe their family's ethnicity and race. Three parents did not respond to this question. We grouped responses to the race and ethnicity questions based on the guidelines provided by NIH regarding race and ethnicity, generalizing based on parents' open-ended responses (e.g., parents who referred to themselves as Vietnamese were categorized as Asian). Sixty-three (78% of the sample) of families that participated identified as white/Caucasian, 5 (6%) identified as more than 1 race or ethnicity, 3 (4%) identified as Asian/Asian American, 3 (4%) identified as Black/African American and 4 (5%) identified as Hispanic or Latinx. None of our families that participated identified themselves as American Indian/Alaska Native or Native Hawaiian/Pacific Islander.

Parents' education levels fell across five categories. Twenty-five parents (31% of the sample) reported they had a Bachelor's Degree at the time of testing. Thirty parents (37%) reported having a Master's degree, 16 (20%) reported having a PhD (or equivalent), 4 (5%) reported having an Associate's degree and 6 (7%) reported having some college or a High School Diploma.

Household income levels fell across six categories. Six parents (7% of the sample) did not report this information. Two parents (2%) reported a household income below $30 K. Three parents (4%) reported $31-50 K. Five parents (6%) reported $51-70 K. Eleven parents (14%) reported 71-90 K. Nineteen parents (24%) reported 91-120 K and 35 parents (43%) reported a household income of $120 K or greater.

Finally, 31 parents (38% of the sample) reported their age between 21 and 35, whilst 50 parents (62% of the sample) reported their age between 36 and 49.

In addition to providing demographics, parents were asked to complete the *Attitudes toward Science* questionnaire (Szechter and Carey, 2009), which is detailed in the section Supplementary material.

Materials, procedure, and coding

The study procedures were approved under Brown University IRB protocol # 2005002720, *Relations Between Parent–Child Interaction During a Remote Activity and Children's Understanding of the Importance of Hand Washing*. All families were tested in their homes *via* Zoom over two sessions. Families were randomly assigned to either the *Watch* condition ($n = 40$) or the *Participate* condition ($n = 41$), described below. We always tested one target parent and a child. Siblings and other caregivers were allowed to be present during the time that the target parent and child watched the video or participated in the demonstration, but they were not allowed to participate in the demonstration, or be present for the other portions of the session. The target parent was required to be present for the activity portion of the study. The target parent did not, however, need to be present for the remainder of the session, during which the child was interviewed. During the first session, the target parent was asked to stay nearby, because the experimenter did ask them one question at the end of the child's reflection. The two sessions occurred between 5 and 16 days apart ($M = 9.24$ days, SD = 1.95). We will describe the procedures for the two sessions below.

First session

Demonstration: Watch vs. participate conditions

In the Watch condition, dyads watched a video of the demonstration (described below) through Zoom's screen share function. The video depicts a woman who introduces the activity by saying "Today we are going to do an experiment. For this experiment, we will be using a bowl (a clear or light-colored bowl will work best), water, pepper, and liquid soap. We will also need a towel." As each item is mentioned, they are brought on to the screen one at a time. The bowl is then placed on a table and the woman says, "To begin, fill the bowl with water." On the screen, the bowl is

FIGURE 1
Screenshot from the video showing the reaction of the pepper to the woman's finger with soap on it being placed in the bowl. The soap breaks the surface tension of the water, which gives the appearance of the finger repelling the pepper.

filled with water. The woman then narrates, "Then grind, shake or sprinkle in pepper until there is an even coat across the bowl." This is again done in the video. The woman continues, "Next, I'm going to dip my finger into the pepper, and watch what happens." She dips her finger in the bowl then takes it out, showing the viewer the pepper stuck to her finger. She continues, "After I wipe my finger clean on the towel, I'm going to try it again, but this time before I dip my finger back in the pepper, I'm going to put soap on it, like this." She puts soap on her finger and says, "Once I have soap on my finger, I'm going to dip it back into the pepper, and watch what happens." She then dips her finger back into the pepper. At this point, the pepper spreads apart from where her finger is located and when she takes her finger out of the water, there is no pepper stuck to it. Figure 1 shows a screenshot from the video of the soap-laced finger in the pepper water. The video shows this reaction three to four times from different angles. The woman wipes her finger on the towel again, and says, "Thanks for watching." The video was about 3 min long. The video (and data associated with this study) can be viewed at https://osf.io/vrf5t/?view_only=fd96158362fe4e96b86c31d5cd1246ea.

In the Participate condition, the parent and child go through the same demonstration on the video, but are led by the experimenter using a script almost identical to what the woman in the video says: "Today you are going to do an experiment. For this experiment, you will need a bowl (a clear or light-colored bowl will work best), water, pepper, and liquid soap. You will also need a towel." The experimenter ensured that the dyads had these materials. She then continued, "To begin, fill the bowl with water. Then grind, shake or sprinkle in pepper until there is an even coat across the bowl. Next, dip your finger into the pepper, and watch what happens. After you wipe your finger clean on the towel, try it again, but this time before you dip your finger back in the pepper, put soap on it, like this (while the experimenter mimed putting soap on her finger) and watch what happens." Between each step, the experimenter paused to ensure that the parent and child engaged in the particular behavior.

We analyzed whether there were differences in the dependent measures described below between the children in the Watch and Participate conditions. In addition to this contrast, we also coded the ways in which parents and children interacted in the Participate condition using the same coding scheme as that of Fung and Callanan (2013); Medina and Sobel (2020). Coders watched the parent and child participate in the demonstration to determine who set the goals for the actions. Dyads were categorized as (1) *Parent Directed*, in which parents mostly set goals for engaging in and completing the demonstration. Parents in these cases usually set out all of the materials, controlled how things were manipulated, including pouring the water into the bowl, grinding the pepper in the bowl, and rubbing the soap on their children's fingers. (2) *Child Directed*, in which parents mostly allowed children to set goals for engaging in and completing the demonstration, which involved letting the child engage in all of the steps without offering help or support, or doing so only if asked. (3) *Jointly Directed*, in which parents supported children and helped where necessary without prompting, but collaboratively engaged in goal setting and actions that moved toward completing the demonstration. The first author, blind to any other aspect of the study, and an undergraduate research assistant, blind to all hypotheses of the study, coded these data. Agreement was 93%, Kappa = 0.82, with disagreements resolved through discussion.

After the dyads watched the video or participated in the demonstration, they were given ~30s to discuss what they watched or saw. During their participation in or watching of the demonstration and throughout the 30s after, the experimenter allowed them to talk to each other about their experience. We specifically concentrated on the extent to which they generated causal utterances, measured by the percentage of the utterances generated by parents or children that were causal in nature. Two research assistants coded these utterances for causal language, as well as other linguistic utterances (see Supplementary material for the full coding scheme). Agreement was 87%, Kappa = 0.80. Disagreements were resolved through discussion with the first author.

Children were then given three other procedures during the first session: a theory of mind battery, a working memory battery, and an interview in which they were asked to reflect on their experience. These are described below.

Theory of mind battery

In the theory of mind battery, children were given three measures from the theory of mind scales (Wellman and Liu, 2004): Knowledge Access, Content False Belief, and Real Apparent Emotions. These were administered as described in Wellman and Liu (2004). Children were also given a measure of second-order false belief (Perner and Wimmer, 1985), using the script from that paper's procedure section. These measures are described in detail in the Supplementary material. To score this battery, we summed the number of measures on which children responded correctly.[3] This battery was scored by an undergraduate research assistant, blind to the hypotheses of the study. A second undergraduate assistant coded 20% of the data. Agreement was 100%.

Working memory battery

Children were given a series of forward and backward digit span tests. For the forward span tasks, children were told a set of numbers, and were asked to repeat those numbers back to the experimenter in the order in which they were presented. Children were first given two trials of a set of three numbers. If they responded correctly on at least one trial, they were given two trials of four numbers. If they responded correctly, the quantity was increased until children were given sets of nine. The backward span task was similar to the forward span task, except that children were instructed to list the numbers in the reverse order in which they were told. On this task, children started with a set of two numbers and proceeded up to nine numbers one at a time if they got at least one of the two trials correct. This battery was scored by an undergraduate research assistant, blind to the hypotheses of the study. A second undergraduate assistant coded 20% of the data. Agreement was 100%.

Reflection

Children were told that the experimenter would ask them a set of questions, and that there are no wrong answers to these questions, and that the experimenter was "just trying to learn about what you think and remember." Children in the Participate condition were asked to tell the experimenter, "What happened in the experiment that you did with your parent?" whilst children in the Watch condition were asked to tell the experimenter, "What happened in the experiment you watched in the video with your parent?" Children were given the opportunity to respond, and the experimenter used further open-ended questions to make sure that the child talked as much as possible about their experience (e.g., "Is there anything else you want to tell me?").

She then asked, "What did you see happen when you dipped your finger/the woman dipped her finger into the water without the soap?" and why they thought that happened, using open-ended prompts (e.g., "Do you want to tell me more?" or "Is there anything else you want to tell me?" or "I'm just trying to get all of your thoughts out of you."). She then asked "What did you see happen when you dipped your finger/the woman dipped her finger into the water with the soap?" and why they thought that happened. Again, open-ended prompts were used to make sure that the child had every opportunity to reflect on the experience, both in terms of what was happening and why. She then asked a set of structured questions: (1) "Did what you see remind you of anything or make you think of anything?" (2) "Did you learn anything?" and (3) "Did you have fun?" If children said yes to any of these questions, she probed for the child to give them more information. Children were then prompted to tell the experimenter anything else that they saw in the experiment or video that they wanted to share. Finally, the parent was asked whether they or the child had seen the pepper demonstration previously.

Here, we focused on whether children spontaneously generated causal or relational connections in their response to the first open-ended question ("What happened in the experiment you watched/did with your parent…") as well as whether children generated a causal explanation in terms of soap or germs in response to what happened when a finger was dipped in the pepper water without and with soap. Children received a score of 1 for each of these opportunities, for a score of 0–3. Other aspects of the coding of the reflections are described in the section Supplementary material. These reflections were scored by the second author and a research assistant, blind to the hypotheses of the experiment. Agreement was 95%, Kappa = 0.92. Disagreements were resolved through discussion.

Between sessions

Directly after the first session, participants were sent an Amazon gift card for $20, and a reminder for their second session. The next day, and every day until (and including the day of) their second session, the target parent was sent an email with a handwashing questionnaire. This email was automatically sent at 8 am ET. In particular, we asked parents to, "Think about the last time [their] child was in a situation where they would typically wash their hands (e.g., before eating, after using the bathroom, etc.)." Parents were then asked to choose whether the child washed, washed only with prompting, did not wash, or that they did not know. If parents indicated they washed, they were asked whether the child used soap (again clarifying if the soap use was prompted or unprompted). The full questionnaire is provided in the Supplementary material. Here, we considered two variables: the percentage of questionnaires on which parents reported that children washed their hands without prompting, and the percentage of questionnaires on which parents reported that if their children washed their hands, they used soap without being told by an adult. These two dependent variables reflect the extent to which children internalized the behavior of handwashing, and the question is whether those behaviors differed based on the participate/watch condition or among the parent–child interaction styles.

Second session

After a brief introduction, the experimenter prompted children to reflect on their first session experience with the activity. The experimenter then administered two additional measures: Contagion Vignettes and the Handwashing and Germ Knowledge Interview.

3 Because the theory of mind scale is progressive, it is also possible to score them as the lowest measure children responded to correctly (so that, for example, if children perform correctly on Knowledge Access, incorrectly on False Belief, but correctly on Real Apparent Emotions, they are not getting credit for passing the higher measure simply by chance). The significant levels of the analyses reported in the manuscript do not change if this alternative system is used.

Reflection

The script for the reflection in the second session was the same as the script for the first session. We concentrated on coding the same causal utterances as in the first reflection. After completing the questions from the script used in the first reflection, the experimenter asked the child, "When do you use soap?" and children were prompted to give as many examples as they could. These reflections were coded by two research assistants, different from those who coded the first reflection. Both were blind to the hypotheses of the study. Agreement on the codes was 97%, Kappa = 0.95. Disagreements were resolved through discussion.

Contagion vignettes

The vignettes were modeled after Blacker and LoBue (2016). Children were introduced to two characters. The experimenter shared her screen, and showed children a picture of a character with their arm in a sling or with a tissue against their red nose and a red thermometer sticking out of their mouth.

For the character with the tissue and red nose, children were told, "This is Sal. Sal has a cold, so Sal has a runny nose, a headache, and sore throat." They were then asked three questions, (1) "How did Sal get a cold?" (2) "If Sal's friend plays with him while he has a cold, will Sal's friend get a cold, too?" and (3) "What if you played with Sal? Would you get a cold, too?"

For the character in the sling, children were told, "This is Danny. Danny has a broken arm, so his arm is swollen and really hurts when he tries to move it." Again, they were asked three questions: (1) "How did Danny get a broken arm?" (2) "If Danny's friend plays with him while Danny has a broken arm, will Danny's friend get a broken arm, too?" and (3) "What if you played with Danny? Would you get a broken arm, too?"

Children received a score of 1 for each question they answered correctly (indicating that they gave a response that was relevant to contagion on the first question for the character with a cold and that was irrelevant to contagion on the first question for the character with a broken arm, and that both they and another person would get sick if they played with the character with a cold, but not that they would get a broken arm if they played with the friend with a broken arm). Thus, children received a score of 0–6 on this measure. These vignettes were scored by two research assistants, blind to the hypotheses of the experiment. Agreement was 89%, Kappa = 0.79. Disagreements were resolved through discussion.

Hand washing and germ knowledge interview

This interview consisted of a set of open-ended questions about the importance of handwashing and how germs are related to the spread of disease. Some of the questions here were modeled after those used by Conrad et al. (2020), see also Leotti et al., 2021).

1. "Why is it important to wash your hands with soap?" For this question, we first categorized whether children generated a relevant response. If they did, we coded that response as to whether it mentioned any of the following: *Behavior*, which involved keeping clean or the act of handwashing (e.g., "To keep your hands clean."); *Self Prevention,* which involved preventing themselves from getting sick (e.g., "So I do not get sick."); *Other Prevention*, which involved preventing illness in others (e.g., "To not spread germs to someone else."); and *Biological Process*, which involved explicit talk about germs, germ transmission or how germs work in the body (e.g., "It gets rid of germs."). These codes were not mutually exclusive.
2. "How do people get sick?" and (3) "What can people do to not get sick?" For both of these questions, we first categorized whether children generated a relevant response. If they did, we coded that response as to whether it mentioned any of the following: (1) Behaviors related to biological processes other than germs/contagion (e.g., not getting enough sleep, not eating healthy, etc.). (2) Behaviors related to contagion (e.g., not washing hands, getting sneezed on, etc.). (3) Physical Processes such as proximity to others (e.g., playing with someone who is sick, spreading germs to someone else, etc.) and (4) Biological Processes, such as talk about germs and how they are transmitted or work in the body (e.g., germs get into your mouth or nose, they attack your healthy cells, etc.). These codes were not mutually exclusive.
3. "Tell me everything you know about germs." We again first categorized whether children generated a relevant response. If they did, we coded that response as to whether it mentioned any of the following: (1) A description of germs (examples include describing them as tiny, as cannot be seen, as being everywhere, as there being good and bad germs, etc.). (2) Behaviors related to germs (e.g., "We have to wear a mask to prevent them going in our mouths"). (3) Physical processes, which involved talk of physical proximity in the spread of germs (e.g., "You can spread germs through touching") and (4) Biological processes, which includes how germs are transmitted biologically or how they work in the body (e.g., germs make us sick, they go in through our nose or mouth). Again, these codes were not mutually exclusive.
4. Coders also noted whether children ever spontaneously talked about COVID-19 or ever referred back to the pepper activity during this interview. This interview was coded by two research assistants, blind to the hypotheses of the study. Agreement was 86%, Kappa = 0.78. Disagreements were resolved by the first author.

Results

We organize our results section around the three research questions described in the introduction. First, we consider whether there were differences between the conditions regarding how parents responded to the handwashing questionnaires

TABLE 1 Responses to the question of whether child washed hands prompted or unprompted (standard deviations in parentheses).

		Do not know	Did not wash	Washed hands with prompting	Washed hands without prompting
Participate condition	Parent directed (N = 11)	7 (13)	13 (18)	35 (24)	45 (28)
	Jointly directed (N = 25)	1 (4)	1 (3)	39 (31)	58 (32)
	Child directed (N = 5)	0 (0)	5 (8)	31 (23)	63 (27)
Watch condition (N = 40)		3 (8)	2 (5)	36 (33)	59 (35)

TABLE 2 Responses to the question of whether used soap prompted or unprompted (standard deviations in parentheses).

		Do not know	Did not use soap	Used soap with prompting	Used soap without prompting
Participate condition	Parent directed (N = 11)	26 (21)	3 (11)	5 (10)	66 (32)
	Jointly directed (N = 25)	3 (6)	0 (0)	13 (20)	84 (22)
	Child directed (N = 5)	10 (6)	0 (0)	12 (13)	78 (13)
Watch condition (N = 40)		4 (11)	6 (16)	7 (17)	83 (26)

between the two sessions, and among the parent–child interaction styles in the Participate condition. That is, does participating in the activity or watching the activity relate to children's subsequent handwashing behavior, particularly regarding soap use, and are differences within the Participate condition related to the parent–child interaction style during the demonstration? Second, we consider whether the conversation that children have with their parents during and immediately following the demonstration or video as well as the reflections children have about the experience relate to their handwashing behaviors. Third, we consider whether any of these relations are mediated by children's understanding of disease transmission, other cognitive capacities, or demographic information.

Parent–child interaction style and handwashing behavior

There were no significant differences between the frequency of parents reporting unprompted handwashing or unprompted soap-use between the Participate and Watch overall, both $|t(79)\text{-values}| < 0.74$, both p-values >0.46. These was our planned comparison. All subsequent analyses should be considered exploratory.

Tables 1, 2 show the percentage of questionnaires on which parents reported that children washed their hands with or without being prompted, and the percentage of questionnaires on which parents reported that their children used soap (prompted or unprompted), looking across the three parent–child interaction styles in the Participate condition as well as the children in the Watch condition. On average, parents completed 8.23 handwashing surveys in the Watch condition (SD = 1.69, Range: 4–14) and 8.27 handwashing surveys in the Participate condition (SD = 2.20, Range 5–15). This was not a significant difference, Mann–Whitney U = 766.00, $z = -0.53$, $p = 0.60$.

We first considered several aspects of the demographics of our sample. This included whether there were differences in Caregiver's gender, age, education level, reported household income, the number of children in the home, the caregiver's experience with science education, and their attitudes about science score. None of these demographic factors were significantly related to children's handwashing behavior, and there were few significant relations with any of the other dependent variables of interest. Please refer to the Supplementary material for detailed analyses and the reporting of these null results.

We constructed two generalized linear models on the percentage of times parents reported their children washed their hands spontaneously and the percentage of time they used soap spontaneously, with age (in months) and parent–child interaction style across the conditions (parent-directed, jointly-directed, child-directed, and Watch condition) as the independent variables. The first model – on children's spontaneous handwashing – revealed only a main effect of age. As children got older, their parents were more likely to report that they washed their hands spontaneously, $B = 0.008$, SE = 0.003, 95% CI [0.003, 0.013], Wald $\chi^2(1) = 10.35$, $p = 0.001$. The second model – on children's spontaneous soap use when they washed their hands - did not reveal a significant effect of age, $B = 0.002$, SE = 0.002, Wald $\chi^2(1) = 0.77$, $p = 0.38$, but did reveal differences among the parent–child interaction styles and the Watch condition. In particular, children in the parent-directed group used soap less frequently than children in the jointly-directed group, $B = 0.19$, SE = 0.09, 95% CI [0.02, 0.36], Wald $\chi^2(1) = 4.54$, $p = 0.03$ and children in the Watch group, $B = 0.17$, SE = 0.08, 95% CI [0.004, 0.33], Wald $\chi^2(1) = 4.03$, $p = 0.05$. No other significant effects were found.

TABLE 3 Percentage of causal language generated by parents and children after demonstration or video and children's causal scores on first and second reflection (standard deviations in parentheses).

		Percentage of parent causal language	Percentage of children's causal language	Children's causal score on first reflection (out of 3)	Children's causal score on second reflection (out of 3)
Participate condition	Parent directed ($N = 11$)	4 (8)	8 (15)	1.45 (1.21)	0.81 (1.07)
	Jointly directed ($N = 25$)	6 (8)	10 (13)	1.48 (0.82)	1.16 (0.80)
	Child directed ($N = 5$)	4 (6)	2 (4)	1.80 (0.84)	1.20 (0.83)
Watch condition ($N = 40$)		10 (16)	9 (14)	1.48 (0.96)	1.30 (0.88)

TABLE 4 Pearson $r(79)$ values and significance levels among variables handwashing and language variables.

	Age	Unprompted handwashing	Unprompted soap usage	Parental causal language	Children's causal language	Causal score, first reflection
Unprompted handwashing	0.34 $p = 0.002$	–				
Unprompted soap usage	0.09 $p = 0.43$	0.22 $p = 0.04$	–			
Parental causal language	0.14 $p = 0.20$	0.29 $p = 0.008$	0.10 $p = 0.37$	–		
Children's causal language	0.21 $p = 0.05$	0.16 $p = 0.17$	−0.03 $p = 0.81$	0.46 $p < 0.001$	–	
Causal score, first reflection	0.27 $p = 0.01$	0.17 $p = 0.13$	0.29 $p = 0.008$	−0.14 $p = 0.22$	−0.03 $p = 0.76$	–
Causal score, second reflection	0.25 $p = 0.03$	0.20 $p = 0.08$	0.11 $p = 0.31$	0.01 $p = 0.985$	0.12 $p = 0.28$	0.46 $p < 0.001$

Language and reflections

We next considered whether the explanations and causal language children heard or generated during and after they participated in or watched the demonstration influenced their handwashing behavior, as well as whether their handwashing behavior was related to the amount of causal information they generated during their reflections. Table 3 shows the percentage of causal language children heard or generated during and after they participated in the activity or viewed the video. This table also shows the causal scores on both the first and second reflection about their experience with the activity. None of variables differed across the three parent–child interaction styles and the Watch condition, all Kruskal-Wallis H(3)-values <2.69, all p-values >0.44 (see Supplementary material for more analyses, in particular analyses of other types of language coded during the interaction, which were all unrelated to children's handwashing behaviors).

Table 4 shows the set of zero-order correlations between the two dependent measures and these measures of language, as well as children's age. As can be seen in the table, there was a significant correlation between the percentage of times parents reported their children washing their hands and using soap spontaneously as well as a significant correlation between handwashing and age. There was also a significant relation between the percentage of times parents reported their children washing their hands spontaneously and the amount of causal language they generated. To isolate the independent effects of these variables, we constructed a generalized linear model on the percentage of time children washed their hands spontaneously, with these three variables. Age had a unique effect on handwashing with older children reported as washing their hands spontaneously more often, $B = 0.006$, $SE = 0.003$, 95% CI [0.001, 0.11], Wald $\chi^2(1) = 6.24$, $p = 0.01$. Parents' causal talk was also a significant predictor, $B = 0.64$, $SE = 0.29$, 95% CI [0.07, 1.21], Wald $\chi^2(1) = 4.91$, $p = 0.03$. No other variable was significant.

As can also be seen from Table 4, children's unprompted soap use was correlated with their unprompted handwashing, as well their causal score on the first reflection (but not the second). To isolate the unique effects of the causal score on the first reflection and parent–child interaction style, which revealed significant differences demonstrated above, we constructed a Generalized Linear Model on unprompted soap use with these variables as independent measure. This revealed a similar pattern of results for the parent–child interaction styles, with children in the jointly-directed dyads using soap more often than children in parent-directed dyads, $B = 0.19$, $SE = 0.08$, 95% CI [0.02, 0.35], Wald $\chi^2(1) = 4.75$, $p = 0.03$ and children in the Watch condition using soap more often than those in parent-directed dyads, $B = 0.17$, $SE = 0.08$, 95% CI [0.01, 0.33], Wald $\chi^2(1) = 4.49$, $p = 0.03$. Children who generated more causal information during their first

TABLE 5 Mean scores on theory of mind, digit span, and contagion measures (standard deviation in parentheses).

		Theory of mind score (out of possible 4)	Forward digit span score (out of possible 9)	Backwards digit span score (out of possible 9)	Contagion vignettes (out of possible 6)
Participate condition	Parent directed ($N = 11$)	1.90 (1.04)	3.95 (0.93)	3.32 (0.75)	5.00 (1.00)
	Jointly directed ($N = 25$)	2.20 (1.19)	4.36 (0.71)	3.20 (0.85)	4.56 (1.44)
	Child directed ($N = 5$)	2.00 (1.41)	4.20 (0.84)	3.30 (0.84)	5.60 (0.55)
Watch condition ($N = 40$)		2.25 (1.03)	4.40 (1.16)	3.29 (0.77)	4.83 (1.17)

reflection also were more likely to used soap spontaneously when washing their hands, $B = 0.08$, $SE = 0.03$, 95% CI [0.03, 0.14], Wald $\chi^2(1) = 8.26$, $p = 0.004$.

Interim summary

So far, we have found, through parent report, that the older children in our sample were more likely to wash their hands spontaneously after bathroom use or before eating. This behavior was also affected by the amount of causal language parents generated after participating in or viewing the demonstration. In contrast, there was no relation between children's age and parents' reports of spontaneous soap usage. Instead, soap use was related to parent–child interaction style and condition, with parent-directed children using soap less often. Moreover, the more causal information about germs or soap use that children generated during their first reflection, which did not differ among the parent–child interaction styles or conditions, related to their spontaneous soap usage. So, while older children might wash their hands more often, soap usage seems more influenced by how parents and children interact during the demonstration.

Individual differences in handwashing behaviors

Our third question examined whether demographic factors or other individual differences were related to children's handwashing behavior. Table 5 shows the average scores on the Digit Span Tests, Theory of Mind Battery and Contagion Vignettes. None of these measures significantly differed among the parent–child interaction styles and the Watch condition, all Kruskal-Wallis H(3)-values <2.75, all p-values >0.43. Children's score on the vignettes significantly correlated with parental report about spontaneous handwashing, $r(79) = 0.27$, $p = 0.01$ as did children's theory of mind score, $r(79) = 0.36$, $p = 0.001$ and their score on the backward digit span measure, $r(79) = 0.35$, $p = 0.002$. None of these variables significantly correlated with parental reports about spontaneous soap usage, all r-values <0.17, all p-values >0.14.

To consider the role of the vignettes and children's theory of mind scores on parental reports of spontaneous handwashing, we constructed a new Generalized Linear Model adding these three independent variables to those that were significant in the analogous model from the previous section (age and parent causal talk). In this model, only parental causal talk was a significant predictor, $B = 0.67$, $SE = 0.25$, 95% CI [0.17, 1.16], Wald $\chi^2(1) = 7.16$, $p = 0.007$. This is consistent with the vignette score, the theory of mind score, and the score on the backward digit span all significantly positively correlating with children's age, all r-values >0.50, all p-values <0.001.

We also considered children's responses to the germ knowledge and handwashing questions, administered in the second session. Table 6 shows the frequency of each response type on the four questions, and the correlations between children's responses and age. None of the response types to these questions, however, were significantly correlated to children's handwashing behavior when controlling for age.

Finally, in the Handwashing and Germ Knowledge Interview, we coded whether children ever spontaneously referred to COVID. Approximately 5% of the children did so, but there was no relation between children talking about COVID during this interview and their handwashing behavior, both $|r(79)\text{-values}| < 0.10$, both p-values >0.41. Further, children never referred back to the Pepper demonstration in this interview, so we did not consider this code further.

Discussion

Getting children to learn about and engage in better hygiene behaviors is a goal for many parents and educators, particularly as it relates to recent events surrounding the COVID-19 pandemic. The current study thus examined whether exposure to a particular at-home activity that represented how using soap helps remove germs from one's finger, affected children's spontaneous handwashing and soap use over the following week.

Translating parent–child interaction practices from hands-on museum settings to the home, we found that how parents and children engaged in the activity together (either by participating in or watching the demonstration) had no effect on children's subsequent spontaneous handwashing, but the way parents and children interacted during their participation in the activity related to children's unprompted soap usage. The content of the conversation, particularly the extent to which parents used causal

TABLE 6 Number of children who generated responses of each type to questions about germ knowledge by type.

Question and type of response	Number (and percentage) of children generating this kind of response	Correlation with age
Why do you wash your hands?		
Behavioral: Children's reasoning is related to handwashing and/cleaning behaviors (e.g., to keep your hands clean, when your hands are dirty, etc.)	33 (41%)	$r_s(79) = 0.19$ $p = 0.08$
Self-preventative: Children's reasoning is related to preventing their own sickness (e.g., so I do not get sick, so I stay healthy, etc.)	40 (49%)	$r_s(79) = 0.41$ $p < 0.001$
Other-preventative: Preventative - Others justifications: Children's reasoning is related to preventing sickness in others (e.g., to not spread germs to someone else, so others do not get sick, etc.)	11 (14%)	$r_s(79) = 0.19$ $p = 0.08$
Biological process justifications: Children's reasoning contains explicit talk of germs and how germs are transmitted and/or work within the body (e.g., it gets rid of germs, soap kills germs, etc.)	61 (75%)	$r_s(79) = 0.10$ $p = 0.33$
How do people get sick?		
Behaviors related to biological processes (other than germs/contagion): Children's response includes behaviors related to health but are not explicitly related to contagion (e.g., not getting enough sleep, not eating healthily, not going to the doctor, etc.)	15 (19%)	$r_s(79) = -0.04$ $p = 0.70$
Behaviors related to contagion: Children's response includes behaviors explicitly related to contagion (e.g., not washing hands, touching something dirty, getting sneezed on, etc.)	40 (49%)	$r_s(79) = 0.28$ $p = 0.01$
Physical processes: Children's response includes physical proximity or spreading through being near/close to someone (e.g., being near people, playing with someone who is sick, spreading germs to someone else, etc.)	34 (42%)	$r_s(79) = 0.36$ $p = 0.001$
Biological processes: Children's response includes explicit talk of germs and how germs are transmitted and/or work within the body (e.g., germs, bacteria, germs get into your mouth or nose, they attack your healthy cells, etc.)	28 (35%)	$r_s(79) = 0.18$ $p = 0.11$
What can people do to not get sick?		
Behaviors related to other biological processes (other than germs/contagion): Children's response includes behaviors related to preventing sickness but are not explicitly related to contagion (e.g., get enough sleep, eat healthily, go to the doctor, etc.)	27 (33%)	$r_s(79) = 0.05$ $p = 0.67$
Behaviors related to contagion: Children's response includes preventative behaviors explicitly related to contagion (e.g., washing your hands, sneezing into your elbow, wearing a mask, getting vaccinated, etc.)	63 (78%)	$r_s(79) = 0.40$ $p < 0.001$
Physical processes: Children's response includes preventing sickness through physical proximity and/or germ spreading (e.g., staying away from others when you are sick, not playing with friends, not sharing drinks, etc.)	40 (49%)	$r_s(79) = 0.25$ $p = 0.03$
Biological processes: Children's response includes explicit talk of germs and how germs are transmitted and/or work within the body (e.g., cleaning to kill germs and/or bacteria, washing your hands to get rid of germs, etc.)	10 (12%)	$r_s(79) = -0.06$ $p = 0.57$
Tell me everything you know about germs		
Descriptors: Children's response includes descriptions of germs (e.g., they are tiny, you cannot see them, they are everywhere, good germs/bad germs, etc.)	47 (58%)	$r_s(79) = 0.35$ $p = 0.001$
Behaviors: Children's responses include behaviors related to germs/germ transmission (e.g., we have to wash our hands, wearing a mask helps, etc.)	34 (42%)	$r_s(79) = -0.01$ $p = 0.92$
Physical processes: Children's responses include talk of physical proximity or the spread of germs (e.g., you can spread germs through touching, if you play with someone who is sick you can get sick, etc.)	23 (28%)	$r_s(79) = 0.25$ $p = 0.02$
Biological processes: Children's responses include explicit talk of germs and how germs are transmitted and/or work in the body (e.g., germs make us sick, they go in through our nose and mouth, etc.)	60 (74%)	$r_s(79) = 0.10$ $p = 0.37$

Note that codes were not mutually exclusive and children could respond in multiple ways, so percentages for each question will not add up to 100.

language during and after their viewing of the video or their participation in the demonstration, also related to whether children engaged in more unprompted handwashing behavior. Further, the amount of causal understanding children generated when they reflected on the experience immediately afterward (but not approximately a week later) related to their unprompted soap use when washing their hands. The extent to which children engaged in unprompted handwashing and soap use did not relate to children's own knowledge of germs or disease transmission.

While we designed the study to examine differences between the participate and watch conditions, the review of the literature on digital learning might suggest that we should not have expected a general difference between these conditions. That said, of interest is the more exploratory differences among the parent–child interaction styles, with the watch condition serving as a potential baseline measure of children's engagement in handwashing. Children whose parents set more of the goals and engaged in more directive behaviors used soap less often during their actual handwashing. These findings parallel cases in which parents taking over an interaction resulted in less engagement in that and related subsequent activities on the part of children (Medina and Sobel, 2020; Leonard et al., 2021; Sobel et al., 2021). More generally, we suspect that these parent-directed behaviors resulted in children believing they have less autonomy in the activity, which might make them less engaged in their participation.

This hypothesis is consistent with two facets of our data. First, children in the three parent–child interaction groups and the Watch condition were equivalent in age, and there was no difference among these groups on any other aspect of children's performance (the theory of mind battery, the working memory tasks, the contagion vignettes, the causal knowledge generated in either reflection, or the percentage of causal utterances made by them or their parents after the demonstration, see Supplementary material for analyses). This suggests that no other aspect of cognition that we measured related to their soap use during handwashing. Second, because the demonstration was about the presence and absence of soap (rather than germs or handwashing) and we avoided sharing the study's explicit purpose with parents, we would not have expected parent–child interaction scores to relate to children's handwashing frequency, which was also evident in these data.

The other significant finding present in these data is that the more children reflected on their understanding of the causal relations inherent in the demonstration, the more likely they might have understood that the demonstration conveyed the importance of using soap during handwashing for the removal of germs from their hands. Critically, this understanding was unrelated to the parent–child interaction style in the Participate condition, and children's understanding of disease transmission and contagion (as measured by the vignettes and the handwashing and germ knowledge interview).

This suggests the possibility that there are two independent mechanisms that relate to children's use of soap during handwashing. The first is a more internal mechanism that relates to children's causal knowledge of the role of using soap. Children's own causal knowledge leads them to behave in certain ways as they explore the world (e.g., Legare et al., 2017). But of importance is that not all measures of causal knowledge related to children's soap use; the only relation was between the amount of causal knowledge generated in the first reflection, not the measures of understanding germs or disease transmission in the second. It is possible that these latter measures did not test enough of children's causal knowledge with sufficient sensitivity to demonstrate positive relations. More likely, however, is the possibility that understanding that germs cause certain kinds of disease transmission is not the same as inferring that the demonstration illustrated how soap use relates to removing germs from one's hands during handwashing. This personal relation might be what is necessary for children to appreciate the importance of using soap during handwashing. Such a hypothesis is supported by Callanan et al. (2017), who found that parents who made personal connections when engaged with their children during informal learning activities had children who were more engaged by the activity. Parents' explanatory talk, in contrast, did not relate to children's engagement.

The second mechanism is a more external, social mechanism, which relates to how parents interact with their children during their participation in the activity. This latter mechanism potentially interacts with the former to produce the extent to which children feel they possess autonomy when engaging with the demonstration. When asked about why one should use soap or how diseases are transmitted, children access the causal knowledge inherent in the first mechanism. But when they actually engage in the real-world behavior of handwashing, the second mechanism related to their autonomy and the social interaction might be more dominant. The more that the parents do for their children during the activity, the less children feel that the activity is for them, and potentially the less they encode from it or the less they are engaged by it (see also Callanan et al., 2020, for a similar finding and similar suggestion about multiple mechanisms relating children's causal knowledge and parent–child interaction during informal learning activities).

Limitations and future directions

An obvious limitation of the present work is that we base our results on a small sample size, and the present investigation needs reproduction. We designed our study to contrast the Participate and Watch conditions. We did not find significant differences between conditions, but did find significant effects among the parent–child interaction styles within the Participate condition. A larger sample size is necessary to contrast the three parent–child interaction styles among one another, as well as with the Watch condition. As a result, the present results should be considered that of exploratory analyses and in need of reproduction. For instance, while we did find significant simple effects in soap use between the parent-directed and jointly-directed groups, we did not find such a difference for the child-directed group (where it would also be expected). However, because so few dyads were coded as child directed, it is critical to reproduce this study with a sample size large enough to perform more confirmatory analyses on the exploratory results reported here.

Moreover, the sample collected was predominantly White, and parents were highly educated. While none of the demographic variables that we analyzed related to our critical dependent measures, it is possible that the sample was not large enough to reveal such differences and these measures could have easily influenced the results. Reproduction of this finding with a larger sample size could also consider this limitation and explore whether there are demographic differences in the ways parents and children interact around hygiene more generally.

Finally, the main dependent variables of interest relied on parental report, which can be a problematic measure. Parents might simply respond with what they think the experimenter wants to hear, or elevate their child's handwashing capacities.

Parents might also be relying on children's descriptions of their behavior, and children might fib about their handwashing behavior. Reproduction could also consider a laboratory-based measure, in which children are required to wash their hands, particularly to see if they spontaneously use soap.

Thus, while the arguments laid out here are grounded in both museum-based and laboratory-based investigations, they would benefit from reproduction with a larger sample using different, but related methods. Such investigations would also address another limitation of this study, which is that we relied on the natural-occurring interaction style between parents and children in the Participate condition, and did not manipulate the autonomy children might have believed they had during their participation. This could also be considered in further reproduction, much like how parent–child interaction to promote exploration or explanation can be manipulated through subtle instructions given to parents prior to their interaction with their children (e.g., Willard et al., 2019; Letourneau et al., 2021). However, one could also consider this particular limitation as a feature: Relying on the interaction style that manifested in our random sample is more representative than empirically manipulating children's perceived autonomy. And to our knowledge, this is the first time that the coding scheme for goal-directedness, which was developed for studying museum exhibits, has been used with a remote activity in the home. We would suggest that the coding scheme transfers to this environment, which increases its application to future datasets.

Conclusion

Previous investigations have found that formal education about soap use actively reduces disease transmission. The present study suggests that a simple, informal, at-home demonstration or video relates to children's soap use during handwashing, at least in the short term. If parents are directive in how they set goals for their children during the activity, the children in the sample showed reduced use of soap in their own handwashing behaviors. While the effect of parent directedness might be small in this sample, it parallels numerous other findings that parent directedness reduces children's engagement and sense of autonomy, and warrants further consideration.

In particular, an interesting caveat to this discussion is that recent findings have suggested ways of reducing parental directedness in museum settings. Sobel and Stricker (2022) showed that presenting families with prompts that encouraged more open-ended collaboration and exploration (e.g., "There is no wrong way to play.") when they initially engaged with exhibit materials reduced parental directedness. It might be interesting to consider modifying the way in which museums present at-home activities, including their current handwashing-related activities, to increase collaborative, playful interactions and encourage causal language among parents through prompts (see also Willard et al., 2019). This could potentially contribute to the efficacy of such programming and increase both parents' and children's authentic engagement with a museum's mission and content beyond the museum walls.

Finally, it might also be important to consider both whether parents' own handwashing relates to children's behavior, and if it changes based on their participation or viewing the activity (following Song et al., 2013). Hermida et al. (2021) demonstrated that not only did children's beliefs about dengue fever change as a result of participating in an interaction with their parents, but parents' beliefs changed as well. While we suspect that all the adults in our sample recognize the importance of soap use during handwashing, a visual reminder about its importance might benefit their own handwashing behavior.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: https://osf.io/vrf5t/?view_only=fd96158362fe4e96b86c31d5cd1246ea.

Ethics statement

The studies involving human participants were reviewed and approved by Brown University IRB. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

DS conceptualized the study, analyzed the data, and wrote the first draft. LS collected all data, designed coding schemes (with input from DS), and supervised all coding and data maintenance. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2022.992710/full#supplementary-material

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Promoting caregiver involvement at the public library: An evaluation of a math and science storytime program for young children

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Introduction: Public libraries are asset institutions that provide important spaces for families to engage in meaningful, authentic STEM learning. However, limited budgets and a model centered on open-access and broad inclusion makes conducting rigorous evaluations in these spaces, such as randomized control trials, challenging. There is a need to consider evaluation designs that consider both rigor and feasibility. The aims of the present study were to: (1) describe an innovative interactive parent–child interactive storytime program, Fun with Math and Science (FMS); and (2) conduct a preliminary evaluation of FMS in a large, urban public library setting, using a quasi-experimental static group comparison design.

Methods and Results: Post-test scores for caregivers who completed the program in the fall or winter (n = 80) were compared to pre-test scores for caregivers who completed the program the following spring (n = 35); Fall/winter caregivers scored higher on program items related to concrete behaviors to support math and science learning, but significant differences were not found on items related to caregiving beliefs or general caregiving practices. Demographic differences were also found related to program outcomes.

Discussion: Results are discussed both in terms of implications for the development and implementation of caregiver-child interactive programming, as well as the use of innovative analytic approaches to program evaluation in community settings.

KEYWORDS

community program evaluation, public libraries, early childhood, school readiness, STEM education, parenting program, parent–child interactions, static group comparison design

Introduction

Children's school readiness skills at formal school entry have been shown to predict children's academic trajectories, with math holding the greatest predictive power of later achievement (Duncan et al., 2007). Unfortunately, many children enter school struggling with the underlying skills important for later math and science achievement. With the growing awareness of the importance of these skills as a part of promoting children's STEM (Science, Technology, Engineering, and Math) achievement, along with the increased attention to the importance of investing in the early childhood years, efforts are being made to more strongly and deliberately incorporate early math and science programming into early learning settings (Brenneman et al., 2009; Hassinger-Das et al., 2020). Much of this attention has been given to formal early childhood education (ECE) settings, such as center-based preschool programs (Clements and Sarama, 2011; Kermani and Aldemir, 2015), with less attention to programming targeting caregivers' capacities to promote their young child's emerging math and science skills. To support early learning within families, there is a movement underway as informal community settings, such as libraries and museums, strive to become more interconnected with the early learning frameworks of their communities (Institute of Museum and Library Services, 2013; Families and Work Institute, 2015). This movement highlights the role of caregivers as a child's first teacher, encouraging libraries and other informal institutions to create experiences that target not only the child, but also teach caregivers how to effectively engage in their children's learning. The current study investigates a public library program designed to teach caregivers how to support their preschool-age child's math and science skills using an interactive, storytime format. Specifically, the study addresses the potential for interactive family involvement programming to promote positive caregiving practices and attitudes important for supporting early math and science learning.

Role of caregivers in young children's math and science learning

Caregivers' expectations for their children predict children's later attitudes about and achievement in math and science domains (Parsons et al., 1982; Crowley et al., 2001; Kleemans et al., 2012; Skwarchuk et al., 2014). For example, in one study, students who perceived support from their parents in math and science concepts tended to feel more efficacious and have positive attitudes towards math and science (Rice et al., 2013). In contrast, Tenenbaum and Leaper (2003) found that mothers who believed their children found science difficult and boring had children who were more likely to report poor ability and low interest in science. Although most of this research is with older children, there is some evidence that expectations are important for younger children as well; indeed, one study found that parents' numeracy expectations about what their preschool child should know predicted children's early numeracy outcomes at the end of kindergarten (Kleemans et al., 2012).

In addition to caregivers' perceptions of what young children should know related to math and science, how caregivers and children spend time together also matters. For example, when caregivers provide math and science activities at home, children's early skills in these areas improve (Kleemans et al., 2012; Skwarchuk et al., 2014; Hart et al., 2016; Daucourt et al., 2021). The work by Kleemans et al. (2012) found that the presence of numeracy activities predicted children's early math skills at the end of kindergarten, above and beyond parent's expectations. Hart et al. (2016) found that parents who reported doing more math activities in the home reported having children with higher math skills; importantly, parent's own anxiety about math was not a significant predictor of child's skills. Further, Skwarchuk et al. (2014) found that both prekindergarten formal (e.g., practicing simple sums) and informal learning (e.g., games with numbers) activities in the home environment predicted children's numeracy outcomes. In fact, a recent meta-analysis conducted by Daucourt et al. (2021) found that the home math environment (including math-activities, beliefs, attitudes, expectation, and interactions) is significantly associated with children's math achievement. Similar results have been shown regarding science learning as well. One recent study demonstrated that preschool aged children who were exposed to science interactions and learning opportunities in the home, including both science content and engineering practice, demonstrated higher levels of science core knowledge (Westerberg et al., 2022). Similarly, Junge et al. (2021) found that parental engagement in science-related activities is associated with preschool children's science knowledge. Engagement in these science activities fully mediated the relationship between parental level of education, parents' interest in science, and home language on child's science knowledge, controlling for children's overall cognitive abilities and gender. Together, these studies emphasize the importance of caregivers' attitudes, beliefs, and practices related to early math and science learning for fostering young children's STEM knowledge and skills. Thus, programs that enhance caregivers' ability to build strong science and math home environments for their children will likely have positive and meaningful impacts on children's early learning.

Promoting positive caregiving related to math and science

With the growing awareness of the value of caregivers in supporting math and science learning among young children for later school success, a burgeoning set of intervention programs for caregivers of young children have emerged, providing preliminary evidence that intervention efforts in both the home and at school can significantly improve caregiving practices and, ultimately, promote children's emerging math skills (Starkey and Klein, 2000; Berkowitz et al., 2015). For example, one randomized trial found that when parents of young children engaged with a mobile-device app program designed to promote math through short numerical story problems during bedtime routines, children performed significantly better on math achievement across the school year, particularly among children whose parents were anxious about math (Berkowitz et al., 2015). In another study, a Head-Start preschool based program designed to engage parents and children together in math learning through biweekly class sessions found that, parents who engaged in the program were better able to support children's math learning than those in the control group (Starkey and Klein, 2000).

In contrast to early math, there is a dearth of research on efforts to promote parent–child learning related to early science skills (see Salvatierra and Cabello, 2022 for a review), which may have to do with a common perception that, compared to other school subjects, science learning is for older children (Andre et al., 1999). An exception is evidence of a children's museum based intervention that found that providing families with enhanced family interactions (e.g., elaborative questions that prompt science thinking) appear to increase parents' ability to support young children's STEM learning (Haden et al., 2014). The current study builds on past work by investigating the potential for a public library math and science program to promote early math and science skills by targeting both parents and children.

The public library as a place for math and science learning

Community settings, like museums and libraries, encourage family involvement in a child's learning through shared interactive experiences. Acting as informal learning settings, these institutions are designed to promote rich conversation and teaching opportunities, and thus hold great potential as settings well positioned to promote caregiver engagement and teach caregivers best practices around supporting their young children's learning of skills that will set a foundation for long-term achievement (see Tenenbaum et al., 2005; Haden, 2010). These caregiver-targeted efforts are largely underway in science and children's museums (Families and Work Institute, 2015) that encourage hands-on learning and shared experiences; however, museums do not exist in every community and are often cost prohibitive because of admission fees. In contrast, public libraries exist in nearly every U.S. community and are characterized as welcoming, no (or very low) cost institutions. It should be noted that disparities do exist in both who accesses and is represented in library settings and materials, due to the pervasiveness of White, middle-upper class norms that are also reflected within our society at-large (Honma, 2005; Gibson et al., 2017; Schlesselman-Tarango, 2017). Although there is an indicated need for more explicit attention toward social justice in these settings, libraries continue to provide a critical role as community anchors. Notably, in recent years, these spaces have shifted their focus from what they can do *for* people to what they can do *with* people, resulting in greater attention to the experiences within the library, including early learning programs (American Library Association, 2015; Clark, 2017).

The experiences, resources, and interactions provided by public libraries fuel a love of learning. The Pew Research Center reports that the majority of parents of young children, especially families who earn less than $50,000, believe that libraries are "very important" for their children, and are interested in more and varied family library services, such as programming (Zickuhr et al., 2013). In response, public libraries continue to evolve to the needs and interests of their communities by tailoring their service model to provide more educational programming in addition to their traditional role of providing information to people, largely through book lending (Ralli and Payne, 2016; Lopez et al., 2017). Early childhood has become an increased focus of public libraries. Indeed, a seminal report called on libraries and museums to strive to provide high quality learning opportunities for young children, arguing that they are essential community resources that are ideal for supporting children's school readiness and caregiver involvement (Institute of Museum and Library Services, 2013). As one example, Play-and-Learn spaces were developed in collaboration between librarians, developmental scientists, and architects to build physical environments within a library (e.g., climbing walls with letters that children can follow to create words) to encourage learning, discourse, and playful interactions (Hassinger-Das et al., 2020). These spaces have been associated with promotive caregiver-child interaction and conversation that can facilitate STEM learning (Hassinger-Das et al., 2020). Providing space for interactive and unstructured play with educational materials is a cornerstone of such programs, allowing children to explore their environments, interact with adults and peers, and grow their love for learning (Gray et al., 2022). Other research has emphasized the importance of using library storytime programs to enhance children's learning. Although historically much of this work has focused on the importance of storytime for enhancing literacy skills (Albright et al., 2009; Campana et al., 2016), Campana (2020) found that librarians were incorporating numeracy and other early math content and skills naturally into storytime programs and that children were demonstrating math behaviors and knowledge during storytime activities. Related to the findings by Hassinger-Das et al. (2020) and Gray et al. (2022) discussed above, Campana et al. (2022) have emphasized the importance of incorporating more in-depth playful learning experience into the traditional library storytime for increasing children's learning behaviors. Research has also shown that parents are drawn to library storytimes for the playful activities and opportunities for interaction (Cahill et al., 2020).

In addition, *enhanced storytime programs* build upon a traditional storytime format, where a librarian reads books and sings songs for a group of children, to pause and talk directly to the adults to teach caregivers tips and strategies. The most well-known enhanced storytime program is Every Child Ready to Read (ECRR), a joint venture undertaken by the Association for Library Services to Children and the Public Library Association. During program sessions, caregivers are led through activities with their children that promote early literacy skills and are taught how to apply and expand on these learning strategies in their day-to-day interactions with children at home. Evaluation results of the ECRR program indicate that the enhanced storytime format does in fact promote family engagement (Neuman et al., 2017), with parents demonstrating an increased understanding of literacy and motivation to support emerging literacy skills in their children

(Stewart et al., 2014). Further, another study found that after the program, parents increased both their use of effective literacy practices and perception of the library as a resource for child learning (Neuman and Celano, 2007). A recent study on another enhanced storytime program that incorporates both parent education tips and caregiver-child interactive play focused on social–emotional development and literacy into a traditional storytime library program, called Books Can…© (Blinded for review), also demonstrated promise for enhancing parents' knowledge, attitudes, and behaviors (Blinded for review). These evaluations provide initial evidence that enhanced storytime programs can promote caregiving practices that encourage early learning.

Interactive caregiving programs also have the potential to enhance positive practices more broadly. As caregivers practice strategies to support their child's early learning, they also likely increase their beliefs, practices, and perceptions of self-efficacy regarding engaging in positive caregiving practices (Welsh et al., 2014); in fact, multiple parenting interventions that target various domains of early learning have also found impacts on broader parenting outcomes, including parenting self-efficacy, child-directed interactions, and relationship quality (Wagner and Clayton, 1999; Pelletier and Brent, 2002). The current study focuses on how a math and science focused enhanced storytime program improves caregiving knowledge, beliefs, and practices related to this domain, as well as positive caregiving more generally.

The program: Fun with Math & Science©

Fun with Math & Science© (FMS; blinded for review) is a 6-week enhanced storytime program for caregivers and their preschoolers delivered by trained library staff. Guided by the National Association for the Education of Young Children's Developmentally Appropriate Practices, it takes a progressive approach to education focusing on multicultural education, constructivism, and child-centered curriculum (National Association for the Education of Young Children, 2009). Through interactive parent–child class sessions, the program aims to improve caregiving beliefs, knowledge, and practices known to promote children's early math, science, and literacy skills. The initial program developed by library staff was rewritten in 2015 by the library's early learning coordinator to align with the state of Arizona's Early Learning Standards for Math and Science and Arizona's School Readiness Framework (Arizona Department of Education, 2013). Through the Partnership for Family-Library Engagement (blinded for review), the authors of this paper were then asked to partner with the library to further refine the program to ensure research-based best practices related to child development and parent engagement were utilized. Each 45-min session covers a different math or science topic, including: using your senses, counting and comparing, geometry and identifying attributes, sorting and classifying, patterning/sequencing/making observations, and measurement/hypothesizing/experimenting. Each session includes: an introduction to the concept of the week, sharing of four practical caregiving tips, interactive adult-child activities, book reading, and active songs. In addition, sessions focus on teaching, modeling, and practicing new skills. Specifically, (a) caregivers are explicitly *taught* current child development information and developmentally appropriate caregiving strategies; (b) instructors *model* the quality adult-child interactions during the course; and (c) time and space is provided for caregivers to immediately *practice* these new skills with their child during activities. After each session, children are given a book and caregivers are given a tip sheet to take home.

Assessing program effectiveness in real-world community settings

Funding for community-based programs continues to prioritize "evidence-based" programming, making evaluations of programs such as FMS© a priority. Pretest-posttest designs are commonly used in community-based research to assess change resulting from participating in a program or other intervention effort, despite their vulnerability to threats of internal (i.e., the degree to which the program causes change in the study sample) and external (i.e., the degree to which the program effect can be generalized to other populations and settings) validity. Rather, this design is used because it is relatively more feasible and requires fewer resources and demands than more rigorous designs that employ a control group. For example, a randomized control trial (RCT) design, often regarded as the gold standard, can best isolate program effects and protect against threats to validity, especially internal validity. However, for many community-based institutions, such as public libraries, limited and fluctuating yearly budgets prohibit rigorous evaluation, including other quasi-experimental designs that use a recruited comparison group (e.g., matched pairs). In addition, because libraries are inclusive community hubs that provide access to programming for all users, limiting service delivery to some families and not others can be unethical.

As such, it is important to consider innovative ways to utilize pre-post data that can increase understanding related to the effectiveness of community programs, because this design is commonly used and is sensitive to ethical concerns and issues of feasibility. The current study addresses this challenge by utilizing multiple waves of pre-post data in an innovative way. Specifically, we conduct a pre-experimental static group comparison design whereby we compare the *post-survey* of caregivers who participated in the program during an earlier time point (fall/winter) to the *pre-survey* of caregivers participating in the program at a later time point (spring). Using this design allows for the latter group to serve as a non-random control group for examining the relationship between program participation and measurable outcomes (Shadish et al., 2001). Importantly, because the control group was drawn from the study sample itself rather than the general public, we have increased confidence that the two groups are comparable. This method has been used in recent evaluations of community-based programs with similar goals, structures, and constraints on implementation (Andrews et al., 2020).

Present study

The present study employs a static-group comparison design to investigate the potential effectiveness of the public-library-based Fun with Math & Science© program on caregiving outcomes among a sample of families with preschool-age children. Specifically, the study asks:

> RQ1: Does participating in FMS improve caregiving knowledge, beliefs, and practices related to math and science, when controlling for family demographic characteristics?
>
> RQ2: Does participating in FMS improve positive caregiving generally (i.e., parenting behaviors, self-efficacy, progressive parenting beliefs), when controlling for family demographic characteristics?

Results of this study have implications for informal learning and community-based efforts to promote school readiness skills for children and supporting caregivers as a child's first teacher. This study also provides a framework for other researchers who, because of practical real-world constraints, are unable to employ resource-heavy experimental design strategies to evaluate a community-based program or service.

Materials and methods

Participants and procedures

A total of 115 families participated in the Fun with Math & Science© program, 80 in the Fall/Winter season and 35 in the Spring season. Demographic characteristics for participating families can be found in Table 1. Data for this study were collected in conjunction with the administration of the FMS programming, which was delivered according to regular library scheduling. The programs were offered in the fall, winter, and spring of the 2015–2016 calendar year at five different library locations and one community center within a single library system. In total, there were 13 different offerings of the 6-week program. For every week that a family attended the program, their child received a book to take home, and parents received a tip sheet relevant to the content for that session. Additionally, in order to encourage participants to attend all 6 weeks of the program, children received an incentive (a small backpack with a science journal, and math and science tools such as a measuring tape, magnifying glass, magnetic wand, bug catcher and eye dropper) if they attended at least five of the six sessions.

TABLE 1 Participant demographics.

	N	%
Total	115	100
Caregiver role		
Mothers	92	80
Fathers	11	9.6
Grandmothers	6	5.2
Other	5	4.4
Race/ethnicity		
White	69	60
Hispanic/latinx	21	18.3
Asian Indian	18	15.7
East Asian	7	6.1
Black	3	2.6
Middle Eastern	2	1.7
Native American	2	1.7
Home language		
English	98	85.2
Spanish	16	13.9
Other	22	19.1
Survey language		
English	113	99.1
Spanish	1	0.1
Highest level of education		
Did not graduate high school	1	0.9
High school degree	3	2.6
Some college	11	9.6
Associates/technical certificate	10	8.7
Bachelors	39	33.9
Maters	36	31.3
Doctoral degree	8	7
Economic hardship		
No difficulty paying bills	75	65.2
Do not expect to experience bad times	104	91.3
Do not expect to go without basic needs met	102	89.6
End up short on money at end of month	12	10.4
Child gender		
Female	128	55.7
Male	90	39.1
Childcare at least 5 h/week		
Yes	116	50.4
No	106	46.1
	M	Range
Child age	3y6mo	1y10m – 5y9mo

After participants registered for the public library program, they were invited to participate in the evaluation study by trained research staff. Using the email addresses from the registration list, caregivers were sent an email with an explanation of the evaluation and a link to the consent form and pre-survey, including demographic questions. Caregivers who had not completed the online pre-survey prior to the start of the program were invited to participate in-person before or immediately after the first session. Reminders were sent *via* email to caregivers who had not yet completed the survey after the first session. Caregivers who joined the program in Week 2 were able to complete a pre-survey at that session, but no one was asked to complete a pre-survey after Week 2 of the program. In the final week of the program, researchers distributed paper post-surveys in-person to all in attendance. Caregivers who did not complete a pre-survey were also asked to complete demographic items at the post-survey. Caregivers who were unable to complete the post-survey in person were sent an email request with a link to the online version of the survey.

Measures

Program MS questionnaire

At pre-and post-test, caregivers completed a 16-item investigator-developed Math & Science Questionnaire: MSQ (Authors, unpublished), that captured beliefs (e.g., "Children learn best when they can explore a math and science concept with their five senses, rather than being directly told about the concept.") and behaviors (e.g., "I use everyday opportunities to incorporate math and science concepts into daily routines with my child.") for supporting young children's math and science learning. Caregivers reported on each item on a 5-point scale from 1 (*Strongly disagree*) to 5(*Strongly agree*). Each item was examined as an independent outcome. Table 2 provides each of the program outcomes with an abbreviation for use in the remaining tables.

Parenting behaviors

Caregivers reported on their parenting behavior using the Raising Children Checklist (RCC; Shumow et al., 1998). The RCC includes three subscales: Firm (5 items; e.g., "Do you try to explain the reasons for the rules that you make?"; $\alpha_{pre} = 0.59$, $\alpha_{post} = 0.54$), Harsh (5 items; e.g., "Do you expect your child to obey you without any questions asked?"; $\alpha_{pre} = 0.60$, $\alpha_{post} = 0.72$) and Permissive (5 items; e.g., "Do you let your child decide what his/her schedule will be?"; $\alpha_{pre} = 0.70$, $\alpha_{post} = 0.62$).

Parental self-efficacy

Caregivers reported on their self-efficacy using the Parental Self-Agency Measure (Dumka et al., 1996). The scale contains 5 items (e.g., "I know I'm doing a good job as a parent."; $\alpha_{pre} = 0.76$, $\alpha_{post} = 0.79$) measured on a 5-point scale ranging from 1 (*Almost never or never*) to 5(*Almost always or always*).

Progressive parenting

Caregivers reported on the extent to which they endorsed progressive parenting beliefs using the Progressive subscale of the Parental Modernity Scale (Schaefer and Edgerton, 1985). The scale includes 8 items (e.g., "It's all right for a child to disagree with his/her parents"; $\alpha_{pre} = 0.64$, $\alpha_{post} = 0.73$) measured on a 5-point scale ranging from 1 (*Strongly disagree*) to 5 (*Strongly agree*).

TABLE 2 Program specific questions and abbreviations.

Full item	Abbreviation
The library is a place I can go to learn about how to be a better parent/caregiver.	Library for caregiving
As a parent/caregiver, I play an important role in my child's math and science education.	Important role in MS
Children learn important math and science concepts before entering kindergarten.	Learn MS before K
It is difficult for parents/caregivers to find opportunities at home to help children develop scientific and mathematical skills.	Difficult for MS at home[a]
Young children learn math and science concepts best through play, rather than in structured environments.	Learn MS through play
It is more important to praise children for getting the correct answer than to praise them for the effort or process it took to arrive at that answer.	Outcome-based praise[a]
It is sometimes better to just tell young children the answer to a question instead of giving children hints or asking questions so they figure out the answer on their own.	Tell children answer[a]
Children learn best when they can explore a math and science concept with their five senses, rather than being directly told about the concept.	Explore MS through senses
I tend to ask my child more close-ended questions (e.g., "What letter am I pointing to?") than open-ended questions (e.g., "What do you think will happen if…?").	Ask close-ended questions[a]
I frequently ask "why" questions to encourage my child to explain their way of thinking about a question.	Ask "why" questions
I use everyday opportunities to incorporate math and science concepts into daily routines with my child.	MS in daily routines
When playing with my child, I typically decide how the activity will go instead of following my child's lead.	Parent-led activities
I feel comfortable talking to other parents about my child's development.	Comfort talking to other parents
I have regular opportunities to interact with other parents	Interact with other parents
I feel prepared to support my child's math and science education.	Prepared to support MS

[a]Indicates negatively valanced program items, where decreases from pre-to post-test are expected.

Covariates

Caregivers reported on their child's age and sex (0 = female, 1 = male) Caregivers also reported on their educational level

(1 = 8th grade or less, 9 = PhD, MD, JD) and their race/ethnicity. Due to small numbers of racial/ethnic sub-groups, we examined differences between White (coded as 0) and Non-White (coded as 1) participants.

Analytic plan

A static-group comparison design was employed. We compared whether the post-test scores for caregivers who completed the FMS program in the fall/winter (coded as 0) differed from the pre-test scores for caregivers who completed the FMS program in the spring (coded as 1). We controlled for child and family characteristics, including child age, sex, caregiver level of education, and child minority status. Analyses were conducted using Stata using full information maximum likelihood to handle missing data, which minimizes bias in parameter estimates while retaining the original sample size (Enders, 2010). There were no significant differences in any demographic characteristics or program outcomes at pre-test between fall/winter and spring participants.

Results

Descriptive statistics demonstrated promising trends, with fall/winter participants reporting higher average levels of positive caregiving outcomes at post-test than spring participants at pre-test (see Table 3). Regression analyses compared post-survey results from fall and winter participants to pre-survey results from spring participants (see Table 4). Significant differences were found for three program-specific outcomes in the expected direction. At post-test, fall/winter caregivers felt 36-SD more prepared to support their child's math and science education ($B = 0.65$, $SE = 0.14$, $\beta = 0.36$, $p < 0.001$), were 0.11-SD more likely to ask "why" questions ($B = 0.16$, $SE = 0.06$, $\beta = 0.11$, $p = 0.01$), and were 0.26-SD less likely to utilize parent-as opposed to child-directed play ($B = -0.56$, $SE = 0.22$, $\beta = -0.26$, $p = 0.01$), as compared to the spring caregivers at pre-test. Significant differences did not emerge on program-specific items related to caregivers' beliefs regarding children's math and science learning. In addition, no significant differences were found regarding caregiving more generally (i.e., parenting behaviors, parenting self-efficacy, or progressive parenting beliefs). Covariates also indicated significant differences in program outcomes, including general caregiving beliefs and styles, and attitudes, knowledge, and behavior regarding math and science (see Table 4 for full results).

Discussion

This study provides initial evidence of the effectiveness of the FMS program in promoting caregiver involvement in children's early MS learning. Results have implications for promoting young children's school readiness in community spaces, such as public libraries. The static-group comparison findings (i.e., using different waves of data collection from one larger study to create a comparison group) heighten the rigor of the study compared to a traditional single group pre-post design, and present a model for other community programs with similar "real world" data collection constraints.

Program outcomes

Math and science practices, knowledge, and beliefs

The results of the current study are promising for the FMS program to increase caregivers' ability to support their child's early math and science learning. In particular, the program outcomes for which fall/winter families demonstrated improvement at post-test compared to the spring families at pre-test were primarily those that centered on program specific behaviors that can be enacted in the home to support early math and science learning. In contrast, program specific outcomes that captured beliefs regarding math and science learning in early childhood did not demonstrate significant differences between the groups. Specifically, caregivers asked more "why" questions to encourage their child to explain their thinking and to take their child's lead during activities. By enacting these behaviors, caregivers likely felt more prepared to support their child's math and science education. Another parent education program, although conducted within the elementary school setting, also found that participating parents demonstrated both increases in the educational activities they engaged in with their children at home, as well as in their role as crucial supporters of their child's learning (Chrispeels and Rivero, 2001).

The fact that significant differences were found regarding program specific behaviors and skills, but not beliefs, regarding science and math learning in early childhood (e.g., Children learn important math and science concepts before entering kindergarten), is consistent with the nature of FMS programming. Through book reading, songs, and interactive activities focused on specific math and science topics (e.g., counting, patterns, asking scientific questions), the program focuses on modeling and practicing concrete behaviors to improve early STEM skills and positive caregiver-child interactions. The FMS program also encourages caregivers to act as co-learners, rather than leaders in their children's play. It is likely that caregivers, especially those who chose to attend FMS, already come into the program with strong beliefs regarding the importance of early math and science skills, but do not feel like they have concrete strategies to support this learning. This is consistent with previous research that has shown consistently high positive beliefs regarding the importance of mathematics for young children and the capacity for young children to learn math, but more variability in parents' reported math practices in the home (Missall et al.,

TABLE 3 Descriptive statistics and correlations for study variables (Spring pre-test *n*=35, Fall/winter post-test *n*=80).

Outcomes	Time	*M*	*SD*	Min	Max	Covariates			
						Parent Ed.	Race[b]	Gender[c]	Age
						r	*r*	*r*	*r*
Library for caregiving	S Pre	4.21	0.72	2	5	−0.35	0.06	0.10	−0.18
	F/W Post	4.26	0.81	1	5	0.34*	−0.02	−0.08	0.07
Important role in MS	S Pre	4.63	0.49	4	5	−0.31	0.12	0.02	−0.96*
	F/W Post	4.81	0.62	1	5	0.55**	0.16	0.10	0.10
Learn MS before K	S Pre⁺	4.65	0.57	3	5	−0.11	0.22	0.07	−0.95⁺
	F/W Post	4.79	0.63	1	5	0.40**	0.26	0.16	−0.02
Difficult for MS at home [a]	S Pre⁺	2.75	1.36	1	5	0.39⁺	−0.32	−0.02	0.91*
	F/W Post	2.29	1.27	1	5	0.01	−0.37*	0.25	0.27
Learn MS through play	S Pre	4.04	0.82	2	5	0.03	0.00	0.00	0.16
	F/W Post	4.38	0.89	1	5	−0.01	0.24	0.17	−0.05
Outcome-based praise [a]	S Pre	2.50	1.38	1	5	0.01	−0.22	−0.06	0.49
	F/W Post	2.51	1.38	1	5	−0.32*	−0.47**	0.19	0.14
Tell children answer [a]	S Pre	2.04	1.16	1	5	0.05	−0.25	0.04	0.06
	F/W Post⁺	1.79	0.98	1	5	−0.07	−0.27	0.00	0.28⁺
Explore MS through senses	S Pre	4.38	0.65	3	5	−0.16	0.07	−0.23	−0.45
	F/W Post	4.56	0.83	1	5	−0.09	−0.04	−0.02	−0.10
Ask close-ended questions [a]	S Pre	3.29	1.16	1	5	0.01	−0.62**	0.29	−0.11
	F/W Post	2.98	1.13	1	5	−0.13	−0.23	0.18	0.11
Ask "why" questions	S Pre	4.00	0.78	2	5	−0.23	0.00	−0.17	–
	F/W Post	4.15	0.64	3	5	−0.12	−0.07	−0.14	−0.13
MS in daily routines	S Pre	3.96	0.91	2	5	−0.33	−0.12	0.10	−0.65
	F/W Post	4.33	0.55	3	5	−0.16	0.11	0.12	−0.12
Parent-led activities [a]	S Pre	2.96	1.20	1	5	0.15	−0.53*	0.04	0.41
	F/W Post	2.35	1.09	1	5	−0.09	−0.48**	0.00	−0.01
Comfort talking to other parents	S Pre	4.25	0.79	2	5	−0.25	0.10	−0.03	0.16
	F/W Post	3.96	0.81	1	5	0.01	−0.02	0.17	0.06
Interact with other parents	S Pre	3.88	1.15	1	5	−0.40	−0.15	0.04	−0.38
	F/W Post	3.96	0.88	2	5	0.02	0.17	−0.12	−0.04
Prepared to support MS	S Pre	4.00	1.10	2	5	0.12	0.06	−0.04	0.38
	F/W Post	4.57	0.57	3	5	0.10	0.14	0.17	0.00
Harsh [a]	S Pre	2.10	0.62	1.25	3.80	0.21	−0.29	0.14	0.57
	F/W Post	2.08	0.52	1.20	3.60	−0.33*	−0.36*	0.29*	0.13
Firm	S Pre	3.50	0.39	2.80	4.00	−0.22	0.31	−0.12	−0.15
	F/W Post	3.58	0.33	3.00	4.00	−0.16	−0.12	−0.14	−0.26
Lax [a]	S Pre	1.82	0.57	1.00	3.00	0.24	−0.23	−0.16	0.82
	F/W Post	1.74	0.45	1.00	3.00	0.20	−0.18	−0.18	0.26
Progressive parenting	S Pre	30.74	4.14	24.00	39.00	−0.04	0.59**	−0.05	−0.03
	F/W Post	31.98	4.23	16.00	38.00	0.41**	0.29	−0.19	0.01
Parental self-efficacy	S Pre	3.97	0.49	2.80	4.80	−0.03	0.17	0.14	−0.20
	F/W Post⁺	3.97	0.51	2.80	5.00	−0.21	−0.16⁺	−0.09	−0.25
					M	6.90	0.41	0.70	3.58
					SD	1.57	0.49	0.46	0.83
					Min	1	0	0	1.87
					Max	9	1	1	5.76

S pre, Spring, Pre-test; F/W Post, Fall/Winter Post-test, ⁺$p < 0.10$, *$p < 0.05$, **$p < 0.01$. [a]Indicates negatively valanced program items, where decreases from pre-to post-test are expected, [b]White = 0, [c]male = 1.

TABLE 4 Changes in program and caregiving outcomes using pre-post design.

Program outcomes	Time (Spring Pre = 0)				Parent Ed				Race (White = 0)				Gender (Female = 0)				Age			
	B	SE	*p*	*β*	B	SE	*p*	*β*	B	SE	*p*	*β*	B	SE	*p*	*β*	B	SE	*p*	*β*
Library for caregiving	0.05	0.04	0.26	0.03	0.06	0.09	0.53	0.12	0.03	0.12	0.82	0.02	0.02	0.15	0.91	0.02	−0.05	0.27	0.86	−0.03
Important role in MS	0.10	0.07	0.18	0.08	0.14	0.11	0.21	0.36	0.05	0.11	0.65	0.04	**−0.17**	**0.03**	**0.00**	**−0.24**	0.11	0.15	0.44	0.09
Learn MS before K	0.02	0.07	0.78	0.01	0.12	0.11	0.27	0.30	**0.20**	**0.07**	**0.00**	**0.16**	**−0.22**	**0.05**	**0.00**	**−0.28**	0.21	0.15	0.18	0.17
Difficult for MS at home[a]	−0.19	0.16	0.25	−0.06	0.08	0.08	0.28	0.10	**−0.49**	**0.16**	**0.00**	**−0.18**	**0.76**	**0.04**	**0.00**	**0.46**	**0.44**	**0.03**	**0.00**	**0.17**
Learn MS through play	0.31	0.28	0.27	0.16	0.00	0.07	0.98	0.00	0.16	0.22	0.49	0.09	0.00	0.28	0.99	0.00	0.20	0.13	0.13	0.11
Outcome-based praise[a]	0.40	0.24	0.09	0.14	**−0.24**	**0.11**	**0.03**	**−0.28**	**−0.78**	**0.19**	**0.00**	**−0.29**	**0.60**	**0.20**	**0.00**	**0.35**	0.26	0.20	0.20	0.09
Tell children answer[a]	−0.11	0.29	0.70	−0.05	−0.06	0.06	0.31	−0.09	−0.34	0.21	0.12	−0.16	0.42	0.28	0.13	0.31	−0.06	0.32	0.84	−0.03
Explore MS through senses	0.15	0.15	0.30	0.09	−0.05	0.08	0.50	−0.10	0.08	0.19	0.68	0.05	−0.07	0.25	0.77	−0.07	−0.09	0.17	0.58	−0.06
Ask close-ended questions[a]	−0.26	0.18	0.14	−0.11	−0.05	0.07	0.51	−0.07	**−0.51**	**0.24**	**0.03**	**−0.23**	0.28	0.22	0.19	0.20	0.38	0.21	0.07	0.17
Ask "why" questions	**0.16**	**0.06**	**0.01**	**0.11**	−0.08	0.05	0.10	−0.20	0.03	0.22	0.91	0.02	**0.00**	**0.19**	**0.00**	**0.00**	**−0.16**	**0.07**	**0.04**	**−0.11**
MS in daily routines	0.28	0.16	0.08	0.19	−0.08	0.06	0.18	−0.18	0.06	0.12	0.63	0.04	−0.23	0.29	0.43	−0.27	**0.22**	**0.07**	**0.00**	**0.16**
Parent-led activities	**−0.63**	**0.22**	**0.01**	**−0.26**	0.04	0.10	0.69	0.05	**−0.73**	**0.29**	**0.01**	**−0.33**	0.16	0.30	0.59	0.11	−0.01	0.11	0.90	−0.01
Comfort talking to other parents	−0.32	0.24	0.18	−0.18	−0.08	0.09	0.39	−0.15	**0.24**	**0.10**	**0.01**	**0.15**	0.12	0.25	0.62	0.12	0.13	0.23	0.57	0.08
Interact with other parents	0.04	0.26	0.86	0.02	−0.12	0.06	0.05	−0.20	0.09	0.17	0.57	0.05	−0.03	0.12	0.82	−0.02	−0.17	0.21	0.42	−0.09
Prepared to support MS	**0.65**	**0.14**	**0.00**	**0.36**	0.04	0.10	0.68	0.08	0.14	0.15	0.35	0.09	0.14	0.37	0.70	0.13	0.11	0.18	0.54	0.06
General outcomes																				
Harsh parenting	0.05	0.09	0.53	0.07	**−0.03**	**0.01**	**0.00**	−0.13	0.02	0.09	0.84	0.02	**−0.10**	**0.04**	**0.02**	**−0.22**	−0.07	0.08	0.37	−0.10
Firm parenting	0.04	0.12	0.74	0.03	−0.05	0.04	0.21	−0.14	**−0.34**	**0.05**	**0.00**	**−0.30**	**0.16**	**0.06**	**0.00**	**0.23**	0.23	0.16	0.15	0.21
Lax parenting	0.03	0.08	0.74	0.03	0.04	0.03	0.21	0.13	**−0.22**	**0.09**	**0.01**	**−0.23**	**0.29**	**0.08**	**0.00**	**0.47**	−0.17	0.12	0.16	−0.17
Progressive parenting	1.00	0.61	0.10	0.11	0.67	0.41	0.11	0.26	**2.32**	**1.14**	**0.04**	**0.28**	−0.69	0.49	0.16	−0.13	**−0.73**	**0.31**	**0.02**	**−0.09**
Parental self-efficacy	−0.03	0.19	0.86	−0.03	−0.03	0.06	0.68	−0.08	−0.11	0.10	0.18	−0.11	−0.13	0.10	0.18	−0.22	0.00	0.07	0.99	0.00

Bold indicates significant findings, [a]indicates negatively valanced program items, where decreases from pre-to post-test are expected.

2015; Şahin Çakır and Uludağ, 2022). In addition, caregiving beliefs are deeply engrained and culturally informed (Sigel and McGillicuddy-De Lisi, 2002), and therefore harder to change. This likely requires a more intensive intervention beyond the scope of the six-week FMS program. However, the significant findings reported here are consistent with other enhanced storytime programs utilizing interactive parent–child activities allowing caregivers to practice new skills in real time (Stewart et al., 2014; Taylor et al., 2020).

General caregiving

It is important to note that we did not see changes in general caregiving practices or beliefs, including parenting style, progressive parenting, or parental self-agency. We expected that as caregivers learned more about child development and engaged in child-directed activities to support their child's learning, they would be more likely to believe in the importance of supporting their children's interests, providing choices, and explaining decisions and rules, as reflected in progressive beliefs and a firm parenting style, in addition to feeling more self-efficacious overall. However, these results indicate that the program may not include enough explicit content to support generalization beyond the specific math and science topics that were emphasized throughout the course. It is also likely that it takes time for caregivers to internalize these ideas and see changes in their children's learning and development. It is certainly possible that if caregivers continued to engage in these behaviors at home beyond the six-week intervention, that they may see the connections between their caregiving more generally and child outcomes. Future program developers or implementers may need to be more intentional in discussing how practices related to supporting math and science learning can be integrated into other domains of caregiving. Changing fundamental practices and perspectives regarding caregiving more generally may require a more intensive and sustained intervention. Finally, as discussed further below, these practices and attitudes may not hold the same relevance across demographic, especially racial/ethnic, groups; careful consideration should be given to choosing program outcomes that are both aligned with the program content and goals, as well as the families whom the program is targeting.

Demographic considerations

It is important to note that considerable demographic differences emerged related to our program outcomes, as indicated through the inclusion of our covariates. Unfortunately, we did not have adequate power to examine whether the library program had differential effectiveness according to such characteristics. However, examining mean-level differences in our outcomes can provide insight regarding how community-based programs, especially those focused on math and science, may best be able to uniquely support particular groups of children and families. This is especially important, as the majority of librarians are White females from middle-class backgrounds (Bourg, 2014; Gohr, 2017), but the families that libraries serve are diverse across a wide range of social identities.

In general, caregivers of boys, caregivers with older children, and caregivers who did not identify as White found it more difficult to find opportunities at home to help children develop scientific and mathematical skills. Additionally, caregivers with lower education levels, caregivers who do not identify as White, and caregivers of older children were more likely to endorse the importance of outcome-based, as compared to effort-based, praise. Racial/ethnic and gender differences also emerged regarding the extent to which caregivers engaged in child-directed play and asked open-ended questions. Each of these caregiving behaviors were taught through FMS tips and activities, so it is crucial to ensure that program content and materials are able to reach families from diverse backgrounds. For example, providing options for downward and upward extensions of program activities can allow families to adapt such activities to be most developmentally appropriate for their child (Klein et al., 2008). In addition, incorporating adequate gender and racial/ethnic/cultural representation in program materials can ensure that families feel like the program content is relevant to them and their home context (Lau, 2006); this can also be enhanced through the involvement of program facilitators who represent the backgrounds and identities of families and children and who are typically under-represented in early childhood spaces, including males and people of color (Phillips et al., 2016). Finally, attention needs to be given to ensuring that materials are accessible for caregivers with lower levels of education; this is especially the case for programs that focus on math and science learning, as these caregivers may feel less self-efficacious regarding math and science concepts themselves (Haylock, 2007). Ensuring the representativeness, accessibility, and cultural relevance of program materials and content will likely promote the increased effectiveness of the program for all families and children, especially those who face disparities at school entry.

In addition to program-specific outcomes, demographic differences also emerged according to parenting styles and beliefs (i.e., firm, harsh, lax, progressive parenting), with caregivers with higher education levels and younger children more likely to engage in firm parenting, and caregivers who do not identify as White and parents of older children more likely to engage in harsh and lax parenting. Caregivers of girls and caregivers who identified as White were also more likely to endorse progressive parenting. Previous research has also found similar differences in parenting style according to demographic characteristics (Okagaki and Frensch, 1998; Shumow et al., 1998; Iruka, 2009; Keels, 2009; Bornstein et al., 2011; Parent et al., 2011; Fasoli, 2014). Historically, firm parenting, whereby caregivers set and communicate clear expectations that children are able to internalize and achieve while also providing opportunities for child autonomy, has been associated with positive academic and behavioral adjustment for young children (Rinaldi and Howe, 2012; Pinquart, 2016); however, this literature has been critiqued for its overreliance of White, middle-to upper-class samples. Research with more diverse samples within the US and across the globe have called into question whether these parenting styles hold the same relevance across cultures, and whether firm parenting is as beneficial, and harsh/lax parenting as detrimental, for non-White, non-middle-class populations (see Pinquart and Kauser, 2018 for a meta-analysis). Therefore, while many parenting programs have aimed to increase firm and/or reduce harsh and lax parenting behaviors, consideration should also be given to the alignment between this aim and families' cultural backgrounds and values that shape parenting styles. Increased scholarship and discourse has focused on promoting anti-racism and social justice within library services and programs (Espinal et al., 2018). One possible approach can be to ensure that program goals and outcomes do not assume White cultural values and beliefs as the norm (Stauffer, 2017).

Lessons learned

This evaluation of the FMS program imparts two important lessons for practitioners and researchers working in community settings. Specifically, it provides guidance on the development and implementation of parent–child interactive programming, as well as a novel approach to program evaluation, moving beyond the traditional pre/post design.

First, our results emphasize the promise for parent education programs that involve the child in interactive activities for enhancing caregiving skills. By providing caregivers with opportunities within the sessions to practice the skills they were learning, we saw significant changes between our treatment and comparison groups on items that directly addressed practices related to children's math and science learning. Considering the age of the participating children (i.e., preschool age), it was important to develop and successfully implement a program that both taught concrete caregiving information and skills, but was also engaging for young children. The interactive storytime format provided opportunities for didactic teaching of program content, book reading, and movement through song and dance, while still having a large block of time for unstructured play and activities to explore the focal math and science concept of the week. In addition, the group-based nature of the program allowed families and children to learn from one another, engage in parallel play, and build relationships over the course of the program. Future program developers should consider a variety of ways to structure programs that facilitate both caregiver and child engagement, as well as skill development.

Second, in our partnership with the public library that developed and implemented the FMS curriculum, the need to consider feasible evaluation strategies was apparent. Although RCTs are a gold standard approach for program evaluation, they are not always practical or possible in many community-based situations, especially without significant additional, and often external, resources. The focus on ensuring internal validity can limit external validity or ignore the realities of providing an accessible and flexible program to families. In addition, the time and resources necessary to conduct rigorous evaluations can be prohibitive, especially as public institutions, such as libraries, grapple with funding concerns or legislation that may impact the timeline for programming and evaluation. At the same time, it is important to recognize the limitations of less rigorous designs, such as pre-post examinations that cannot control for issues such as history or maturation. Employing more rigorous evaluation designs, such as the static group comparison presented here, that both meet the needs and reality of community-based organizations and reduce methodological concerns, is crucial to engage in participatory work between academic and public partners. In this case, because of the staggered delivery of the program, we were able to create a comparable control group within our sample, without limiting the families who received the program or the timeline for receiving it. Our approach is more rigorous than a typical static-group comparison that utilizes a general community sample for a comparison group, as they likely differ across a variety of characteristics, most importantly their desire to participate in the program. Various research designs exist that can be employed to meet the needs of community organizations and researchers implementing and evaluating a wide array of programs (Shadish et al., 2001). To do so, all partners must understand both the needs and realities of the community setting and the population it serves, as well as the expectations for conducting research in that setting to learn about the potential effectiveness of the program on identified outcomes.

Limitations

Although this study provides important information regarding the effectiveness of the FMS program for caregiving behavior, it is not without limitations. First, our study sample was relatively small to begin with and was even smaller after using one of the time-points of data as a comparison group. As a result, the study has low power, increasing the likelihood of undetected or under-detected effects. In addition, our findings may be limited by selection bias, as parents who knew about and elected to enroll in the program may score higher on some of the practices measured than the general population. Therefore, it is encouraging that significant results did emerge; however future studies should replicate these findings with a larger sample of families, including those who may not have known about the program on their own. As a result, all findings presented here are exploratory in nature and should be interpreted conservatively.

Second, the participants in the study were relatively homogenous, especially in terms of gender and education-level; results may not generalize to male caregivers, families with low levels of education, or racial/ethnic groups not well represented in the study (e.g., Black, Native American families). Future work to evaluate the effectiveness of this program would benefit from recruiting a more diverse community sample of parents and young children including those who do not frequent the library setting. This may be achieved by ensuring that library-based programs, such as FMS, actively engage in anti-racist and equity-explicit approaches in both content (e.g., incorporating materials that reflect the background and values of families) and delivery (e.g., minimizing barriers to participation).

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Third, the data collected were all parent-report and the Math & Science Questionnaire used to capture program specific beliefs and practices is an investigator-developed measure used here for the first time. While this measure showed high internal consistency and predictive validity, its convergent and discriminant validity have not been tested. Future studies would benefit from the use of multi-method assessments of caregiving and need to examine the relationship between scores on the MSQ and well-established measures of positive caregiving to confirm its overall validity.

Finally, although we believe the static-group comparison research design added methodological rigor to the study (compared to a traditional pre-post design), it is not without limitations. Due to the correlational nature of the study, this evaluation was unable to isolate program impact. Therefore, a more rigorous experimental or quasi-experimental design to evaluate program effectiveness is needed. Despite the limitations associated with utilizing a post-test only design, strengths of the present study were the inclusion of covariates (i.e., parent education, race/ethnicity, child age, child gender) and a novel analytic approach to analyzing the data. As a result, the results are stronger than traditional mean comparisons (e.g., t-tests) because the estimates take into account outside factors that may be associated with caregiving outcomes and create a comparable control group.

Conclusion

Despite the above limitations, the present study contributes novel findings regarding the promise of providing authentic STEM learning within community settings, through an enhanced storytime format. We find preliminary evidence that FMS can impact concrete caregiving behaviors related to early math and science learning. Due to its openness and accessibility, the library provides an exceptional opportunity for families to engage in programs to support their young children's math and science learning. However, most of the families that participated in the program were White and of middle-high socio-economic status, so attention should be given to techniques that could reduce systemic barriers that might prevent families from participating in library programs and that may enhance alignment between families' backgrounds and values with the program content and goals. Additionally, the nature of library programming also presents challenges for conducting a gold-standard rigorous evaluation; this is a concern likely shared by program implementers and evaluators in other community settings. Therefore, this paper emphasizes how other research designs – in this case, the static-group comparison design – can meet the needs of community-based programs and their participants, while still increasing the methodological rigor beyond a typical pre-post evaluation.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the Arizona State University Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

Author contributions

LG, MT, MP, and MW: study conception, design, and draft manuscript preparation. LG, MT, and MP: data collection, analysis, and interpretation of the results. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Talk of the Town mobile app platform: New method for engaging family in STEM learning and research in homes and communities

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Children do not just learn in the classroom. They engage in "informal learning" every day just by spending time with their family and peers. However, while researchers know this occurs, less is known about the science of this learning—how this learning works. This is so because investigators lack access to those moments of informal learning. In this mini-review we present a technical solution: a mobile-based research platform called "Talk of the Town" that will provide a window into children's informal learning. The tool will be open to all researchers and educators and is flexibly adaptable to these needs. It allows access to data that have never been studied before, providing a means for developing and testing vast educational interventions, and providing access to much more diverse samples than are typically studied in laboratories, homes, and science museums. The review details the promise and challenges associated with these new methods of data collection and family engagement in STEM learning sciences.

KEYWORDS
informal learning, parent–child interaction, methods, research tools, developmental psychology, education

1. Introduction

"Informal learning" is loosely defined as learning that occurs outside the classroom or structured educational tasks. Researchers who study the science of learning and STEM education are well aware that informal learning occurs and that it is a critical contributor to children's knowledge and competence (Falk et al., 2007; Powell and Peet, 2008; Jones et al., 2013; Morris et al., 2019). However, informal learning is intrinsically difficult to study. By definition it cannot be studied in the classroom. It occurs, often unpredictably, through media content, social interactions with peers, self-guided exploratory play, and—as in the focus of this paper—it can occur in natural interactions between children and parents or caregivers as they go about their everyday lives.

There have been several different kinds of efforts to capture informal learning between parents and children in various contexts. One approach has been to study informal learning in the context of science museums (Callanan, 2012). These studies often involve recording of children's interactions with their caregivers at specific exhibits, with the goal of studying what children learn from those exhibits and how they engage with them (e.g., Thomas and Anderson, 2013). However, these studies face a number of important limitations. The first and most obvious is that they are restricted to the exhibit in question. In addition, the pool of participants is restricted to families in a given area who visit that museum, which provides a somewhat restricted population that may not be fully representative of the breadth of informal learning experiences (though more representative than most in-lab studies; Callanan, 2012).

A second approach is to study informal learning through parent–child interactions in the home with intensive at-home recording studies, using tools like LENA (Ganek and Eriks-Brophy, 2018) or corpus studies based on previous at-home recordings (e.g., using the CHILDES database, MacWhinney, 2000; or Databrary, Dressler, 2015). This approach circumvents the topic-specificity of museum-based studies, but is still limited by a likely non-representative population and challenges in isolating relevant data. With hundreds or thousands of hours of recordings, identifying relevant segments for informal learning about a specific topic is challenging and time-consuming. Finally, as a purely observational approach, these at-home recording studies are not well-suited to interventions, limiting the scope of the questions that can be asked using these methods.

A third approach is to use diary or beeper-style studies (modern versions typically use text messages or emails), in which parents are asked to answer questions about their children's activities at various intervals (e.g., Boyatzis and Janicki, 2003). These studies are, in principle, more capable of supporting interventions and can be designed to target specific types of parent/child activities (e.g., asking parents to complete a survey when their child is doing a STEM-related activity), but the data are limited and indirect (Morris et al., 2019). Asking a parent to report a child's behavior rather than a researcher observing behavior directly often means that important nuances are being lost, and the act of filling out the diary or survey itself can distract the parent from interacting with their child.

We present a novel tool and novel approach for studying informal learning through parent–child interactions. Our tool is a research platform we call "Talk of the Town." It consists of a mobile phone app controlled by a secure server. The basic idea of the platform is as follows: Parents download the app and sign up for a study. They then are presented with notifications asking them to record a short (~5-min) conversation with their child. These conversations can be based around specific prompts designed by the experimenter (e.g., as an intervention or experimental manipulation), or they can simply capture whatever is being discussed at that time. Parents can then answer a couple of short questions (e.g., about what they were doing during the recording), and upload the recording and their responses securely to a server where they can be analyzed. Figure 1 presents a summary of how the platform functions. This abbreviated description omits a great many important details that we will elaborate below, but it should be clear already that the goal is to capture rich, naturalistic data from a broad population[1] in a minimally intrusive way, with a flexible tool that can be used to study many different facets of informal learning in STEM and in other domains. This tool will be deployed to the broader scientific community and is designed to be flexibly adaptable to researcher or educator needs. Because researchers and educators can choose what prompts to deploy, it can be flexibility used for researchers with whatever research question they choose to explore or it can be developed by educators, as a tool for prompting (and recording) STEM engagement.

We start by describing the mobile app component in greater detail. Just using a mobile phone app avoids many of the limitations of previous approaches. The app goes wherever the parent goes, without requiring the researcher to provide any additional hardware or specialized equipment, and so it can capture data anywhere and anytime the parent and child are together (and the parent wants to engage with the app). When parents choose to do an activity, the app presents a simple recording screen (Figure 1 includes a small screenshot from the current development build of the app). The recording screen includes a prompt which can be generic or targeted to a specific topic of conversation. The parent can then record a conversation for up to 5 min. After finishing the recording, the parent can listen to it themselves, fill out a short survey describing what they were doing, and choose to upload the recording or not. This design addresses many potential privacy and confidentiality issues: Not only must the parent deliberately engage with the task and start the recording, they can also choose whether to provide the recording to researchers or not after the fact.

However, simply having the app on hand would mean that parents have to remember to use it. Therefore, the app uses notifications to prompt parents to record conversations with their child. These notifications can be triggered by several different factors. First, they are only presented during times that the parent specifies they are able to do an activity with a child in an eligible age range, which they indicate during the onboarding process. Second, these notifications can be timed based on researcher-specified intervals and tied to specific tasks. For example, a researcher could create a longitudinal study that provides a notification to the parent at regular intervals triggered by completing the previous session (see Figure 1). This can also be used for intervention studies: The prompt for an activity can be a specific educational task, varied across participants, and researchers can examine whether that intervention has an impact on subsequent conversations. Third, the notifications can be triggered by a location, such as an exhibit at a museum, a historical statue in a park, or even the more day-to-day such as grocery stores or libraries.

The ability to link notifications to location specific sites is a unique (as far as we know) feature of the platform. "Geofences" are simply a set of GPS coordinates and a radius. The app is designed such that, if the parent provides location permissions (also part of the onboarding), if the phone detects that it is in proximity to one of a large database of landmarks provided by researchers, it will present a notification and a location-specific activity for the parent to do with their child. One can think of this as similar to some museum-based studies, with three key differences: Rather than placing a recording system in the exhibit, it is in the hands of the parents; rather than being restricting in time to just the moment of museum interactions, automated follow-ups can be delivered hours, days, or weeks later; and rather than being restricted to a handful of exhibits or a single museum, it can be applied to the entire world. While particularly useful for outdoor landmarks, we have also discussed the possibility of partnering with certain museums to use "beacons" placed in specific exhibits to use the app as an alternative to a standard museum-based study. Ultimately, the app just needs to know that it is in proximity to a potential activity location, and it can notify the parent to prompt them to engage in an activity with their child at that location, which the app can then record.

The data that the app provides also strikes a careful balance. Like home-recordings, the data that the app captures is very rich, consisting of conversations between parents and children, as well as capturing

1 The obvious equity-limiting factor of this platform is that only families with smartphones are able to use it. However, smartphones are increasingly ubiquitous (more than 85% of Americans now own a smartphone, Pew Research Center), and future development can ensure compatibility with older phone models.

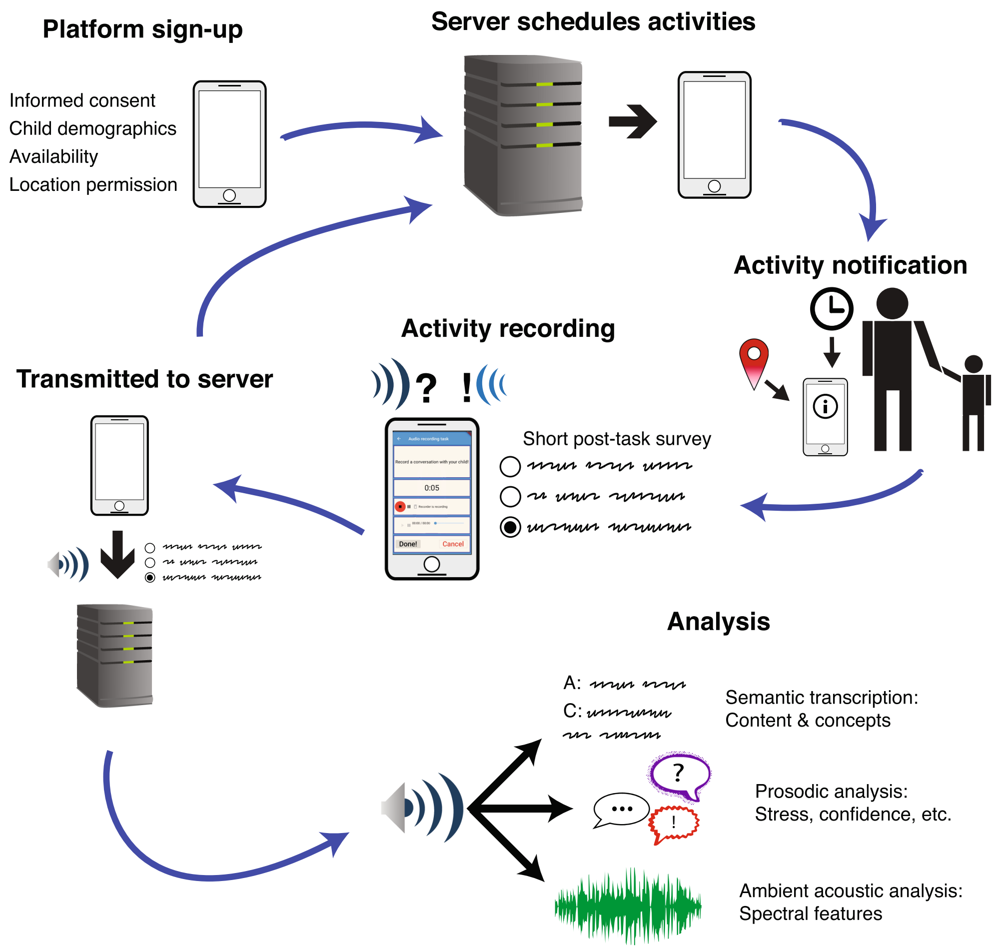

FIGURE 1
Summary of the workflow of the Talk of the Town platform, from initial sign-up to data analysis. See text for more detailed descriptions of each step.

some information about the ambient environment (e.g., indoors vs. outdoors; Van Hedger et al., 2019a,b). However, because the recordings are short, parent-initiated, and tied to specific prompts, they are much more focused and require less processing to isolate relevant interactions. In addition, researchers can include short surveys for parents to fill out after the recordings, which can provide valuable metadata about what the parent and child were doing at the time, levels of engagement, and more.

The platform's design is intended to be highly flexible for researchers or educators. These investigators only ever need to interact with the server side of the platform to develop their specific use content. The server, the Sage Bionetworks Bridge platform (Sage Bionetworks, 2022), is designed for use with medical research apps, and therefore has a level of security and encryption more than suitable for behavioral research. Investigators can specify the parameters of "assessments" on the server, such as the content of a prompt, the timing of notifications, and any geofences it should be tied to (as well as the geofences themselves). This information is then transmitted to the app any time the parents log in to the app, updating the app's internal library of tasks and scheduling future notifications. Notably, this does not require the app itself to undergo a full update. Rather, one can think of it like a waiter at a restaurant presenting an order to the kitchen: the kitchen already has the tools and ingredients to make the dish, they just need to be combined and presented back to the customer. This means that the types of tasks available are restricted to the previously described recording activities and short surveys, but it is easy to add new studies or change existing studies on the fly.

A potential key benefit of the app is that, with careful recruitment, participants may represent a broader and more representative sample of the population than typically found in laboratory studies that tend to overdraw from higher SES populations in university and city centers (Fernald, 2010). Because anyone with a mobile phone can sign-up to engage with a study run on the app, families can participate without concern of transportation into a lab or being locally-university based. Indeed, studies comparing online data collection to in-lab collection has already revealed better representation through online methods that require computers (e.g., Scott and Schulz, 2017). We believe that by further lowering barriers (users without computers, who have phones can participate), we will be able to achieve even greater representation. Furthermore, additional languages can be relatively easily available, and we are looking to develop a Spanish version in the next year. Finally, we note that labs can offer financial incentives to participating families, which may increase participation from under-resourced communities.

2. Challenges and pitfalls

Naturally there are challenges that come with the development of any new technological tool. In the case of a mobile-app-based platform like this one, the first challenge is the development and maintenance of the app itself. Fortunately, because the functions of the app itself are relatively simple, the first author was able to do most of the initial development in the Flutter framework (Google, 2022), but professional assistance is required to polish the app to the point that it can be released on an app store, which is a moderate investment. However, initial development is not enough. Every new version of iOS or Android operating systems, or updates to the code libraries that support critical functions like notifications or sound recording, will require some degree of maintenance work on the app itself at regular intervals, and in turn require a consistent investment of resources. The plan is to make the app itself open-source, so that other research groups can create their own "clones" of the app, but this should not be undertaken lightly. Mobile apps, in general, require a greater degree of development effort than a web-based app (e.g., Chan et al., 2017; Webster et al., 2017).

The second challenge is recruitment and retention of participants. In conversation with other groups that have attempted app-based research in the past (see acknowledgements), this has consistently surfaced as a major challenge. To get parents to download an app and continue to use it, the app must offer the parents something in return. That can take the form of compensation or prizes for their children, but ideally *engaging with the app itself* should be valuable to parents. We intend our use of the platform to present fun activities for parents to do with their children, such as scavenger-hunt-like activities at zoos, museums, and parks using the geofencing system, as well as education-focused activities as part of research studies, but it will be up to individual investigators to consider how they may choose to recruit users. Since the primary unit of activity in the app is a parent/child interaction, we want to make those interactions fun and rewarding for both parents and children, and by doing so, we hope to collect a great deal of data simply because it is something parents *want to do*.

However, after surmounting the challenges in launching the app and getting families to participate, there is a third challenge to consider: processing the data. If the app is very successful, vast amounts of rich audio data will require processing. The richness of parent/child conversations is certainly a boon from a research standpoint, but practically speaking it is also a burden. To manually transcribe hundreds or thousands of recordings, even short ones, requires thousands of person-hours and is difficult work. To get ahead of this problem we have been developing a partially automated data-processing work-flow, completely divorced from the app and platform itself. To keep the app simple, all it does is upload the data. Once we have the data in-hand, we have developed a workflow that starts with an automated transcription.[2] The transcript produced by this system is then imported into ELAN (2022) for human-proofing, which in early pilot runs has taken half the time or less than transcribing from scratch. These tools will also be available to promote Open Science. This is certainly not the only solution to the problem, but any lab that intends to collect this kind of rich data on a large scale needs to be ready to process it, and it is a non-trivial problem.

2 To go into some detail, after exploring several options we found that (at the time of this submission) Microsoft's Azure Speech-to-Text system was better at handling children's voices than most of the alternatives, which is naturally a critical concern for our purposes. Furthermore, because our institutions have an agreement with Microsoft, we are able to run this service in a locally-hosted "container," satisfying privacy and confidentiality rules.

3. Unique research opportunities

Why is it worth going through all this trouble? In short, because the Talk of the Town platform provides a ground-breaking opportunity to study informal learning in greater depth and with a broader population than ever before. The app's simple design nonetheless supports substantial flexibility, thanks to the ability of the server to specify content, target populations, and track completion of specific tasks. Using the platform it is possible to conduct experience sampling studies, longitudinal studies, and simple intervention studies. With the geofencing system, truly unique types of studies that capture, naturally, when and how families interact with certain landmarks in their environment can be carried out, targeting learning in time and space. The data that will be captured by the app will ultimately form a corpus of recordings connected to demographic, timing, and location metadata that will provide opportunities for re-analysis on a variety of issues. Semantic content, prosodic content (including vocal stress markers), and ambient acoustic environment are accessible to researchers. Furthermore, the app offers the potential for valuable collaborations with zoos and museums all over the world without requiring prohibitive investment of space, money, or time by these sites nor by principal investigators.

Finally, from a practical standpoint, professionally developed apps cost hundreds of thousands to millions of dollars, and developing a secure server from scratch would be no less expensive. The app uses open-source tools and only required advanced but amateur programming skills to develop to the point of basic functionality.[3] While some professional development will be needed to polish and improve the app in the future, it should not require full-time professional attention to maintain. As for the server, using external options like the Sage Bionetworks Bridge is not free, but the cost of an annual research agreement is far preferable than the time and money investment required to build such a system from scratch. In particular, being able to lean on others who have experience handling sensitive medical data makes the regulatory aspect much easier to deal with, even when capturing personally identifiable data from a vulnerable population. The data recorded by the app are encrypted and transmitted securely to a heavily-protected server overseen by professional security staff.

4. Conclusion

The Talk of the Town platform is an example of a new kind of research tool that will be invaluable for understanding the role of informal learning in STEM education and success. While we hope to make our specific platform available to a broad range of collaborators, we hope that our description of its development and underlying systems will also inspire other groups to build on our efforts and develop their own tools to address specific questions or issues. The potential of mobile-app-based research for the science of learning is tremendous, but the successes to date have been few and relatively costly in time, effort, and expertise (e.g., Morris et al., 2019). It is easy to see why this kind of research is not yet

3 Admittedly not quickly; it took about a year and a half to develop.

widespread, given the enormous up-front investment and perpetual challenges of recruitment, retention, and maintenance. However, it is our belief that a single successful broad deployment of a platform like Talk of the Town could yield such a bounty of novel and valuable insights into informal learning through parent–child interactions that it will open the floodgates to a whole new generation of research programs on informal learning more broadly, and perhaps revolutionize how researchers approach the science of learning as a whole.

Author contributions

JK drafted the manuscript and created the figure. JK, IB, PS, and EB revised and edited the manuscript. All authors contributed to the article and approved the submitted version.

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Presenting wicked problems in a science museum: A methodology to study interest from a dynamic perspective

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Science centers and science museums have an important social role in engaging people with science and technology relevant for complex societal problems—so called wicked problems. We used the case of personalized medicine to illustrate a methodology that can be used to inform the development of exhibitions on such wicked problems. The methodology that is presented is grounded in dynamic theories of interest development that define interest as a multidimensional construct involving knowledge, behavior (personal and general) value, self-efficacy, and emotion. The methodology uses a mixed method design that is able to (1) study the predictive effects of background variables on interest, (2) study the interest dimensions predicting individual interest, and (3) identify the most influential interest dimensions. We set up focus groups (N=16, age=20–74, low SES) to design a survey study (N=341, age 19–89years olds with a broad range of SES) about people's interest in personalized medicine. Results of a network analysis of the survey data show that despite the variety in emotions and knowledge about subtopics, these dimensions do not play a central role in the multidimensional interest construct. In contrast, general value and behavior (related to understanding scientific research) seem to be interesting candidates for eliciting situational interest that could have an effect on the more long term individual interest. These results are specific for the case of personalized medicine. We discuss ways in which results of studies with the presented methodology might be useful for exhibition development.

KEYWORDS
informal STEM learning, individual interest, wicked problems, network analysis, visitor studies

1. Introduction

Wicked problems, such as digitization, climate change or future healthcare, do not have clear solutions, but a variety of insights into what the core of the problem is and what the directions are in which solutions should be sought. Multiple perspectives, including a scientific perspective, are relevant for understanding wicked problems. Science centers and science museums have an important social role in engaging people with science and technology relevant to these complex societal problems (Rittel and Webber, 1973; Dillon, 2017).

The development of interest for topics, such as wicked problems, are believed to have multiple phases. The main subdivision made is in situational and individual interest (e.g., Hidi and Renninger, 2006; Ainley and Ainley, 2015), but also three stages have been distinguished (Krapp, 2002b). Situational interest "describes a short term psychological state that involves focused attention, increased cognitive functioning, persistence, enjoyment or affective involvement, and curiosity" (Schiefele, 2009, p. 198). Situational interest needs an external trigger to arise and lasts relatively shortly, for instance for the time span of the activity or the learning event. Individual interest, on the other hand, "refers to a long-term disposition to engage with a particular practice or set of activities" (Azevedo, 2018, p. 110). Someone with an individual interest in a topic engages with the topic without needing external support. The general assumption of this multiple phase model is that a repeated triggering of situational interest precedes the development of a more sustained and ultimately an individual interest. Individual interest is not only thought to be relatively stable, but is also marked by (positive) affect toward the topic, by an increased knowledge about and valuing of the topic (Hidi et al., 2004; Schiefele, 2009). That is, an interest in a topic involves multiple dimensions of cognition, behavior and affect, which form a complex, dynamic interplay (Sachisthal et al., 2019). Retrospective interviews with individuals with an interest in nature point to the importance of overlapping knowledge, skills and identities in the development of an individual interest (Hecht et al., 2019). For science, the importance of the family in shaping students' engagement, aspirations and achievement, and thus their science interest was well-established (Archer et al., 2012). Archer et al. (2012) explain the complex process of developing an interest in science by the Bourdieusian framework. It is the interplay between the family science capital, the social, economic, and cultural resources that facilitate science achievements, and the habitus, the values, sense of identity, and practices of the family, that shape the development of an interest. Hence, formal education is expected to be just one step in the development of an individual interest in a particular subject, especially for wicked problems involving also a scientific perspective. And thus, informal STEM experiences may importantly contribute to the development of an individual interest. Some museum programs have designed interventions aimed at developing an individual interest in science by intervening on multiple dimensions simultaneously, such as the program of Habig and Gupta (2021) at American Museum of Natural History (New York, United States). In general, however, museums and other informal learning institutions typically contribute to interest development by offering a context for learning about a topic that is joyful, that asks for cognitive engagement and is driven by curiosity (Hecht et al., 2019), that is by triggering situational interest.

How can science museums decide which interest dimensions, including (personal and general) values, emotions, self-efficacy, behavior, and knowledge (Sachisthal et al., 2019) should be highlighted in the exhibition to aid the development of individual interest? Having a focus on complex problems here, first it is important to take into account that interest dimensions may differ across subtopics (Betten et al., 2018) and that opinions may be shaped by background variables such as socioeconomic status (SES), education, and local neighborhood (Bouma et al., 2020). With the goal of identifying dimensions that play an important role within individual interest, we draw on a psychometric network perspective, which allows for the study of psychological constructs such as attitudes (Dalege et al., 2016), and individual science interest (Sachisthal et al., 2019, 2020). In a network of individual interest in a wicked problem, the different interest dimensions need to be included, but so do subtopics of the wicked problem in question (Betten et al., 2018). The dimension lying at the heart of the individual interest can then be identified—which may provide insights into possible leads that can be used to develop exhibitions on the wicked problem.

The aim of the current study is to develop a methodology for science museums to identify topic-specific leads to improve the context for triggering situational interest that could contribute to the development of an individual interest of a diverse population. The involvement of people of all ages, backgrounds and stages of life is an important goal for museums (Falk and Dierking, 2019). The design of the exhibition to trigger the situational interest of a variety of people is a first step in that direction. The methodology we follow adheres to a dynamic conception of interest (Ainley, 2017), where interest can be seen as a network of nodes that represent subtopic-specific dimensions (e.g., values, beliefs, emotions, knowledge, and behavior) that mutually influence each other (Sachisthal et al., 2019). The structure of a psychometric network is given by the interactions of the nodes, that is, the partial correlations of pairs of nodes corrected for all other nodes. The so-called central node has the greatest impact on the network as a whole. Central nodes may be effective targets for interventions (Borsboom and Cramer, 2013; McNally, 2016; Zwicker et al., 2020), in our case to stimulate individual interest development. With the same reasoning, nodes that are not well connected to the rest of the network are not expected to be effective subtopic-specific dimensions to contribute to the development of individual interest, not saying that they could not elicit a situational interest. For example, Sachisthal et al. (2019) show that locus of control and self-reported pro-environmental behavior were the most central constructs of interest within a network of climate change beliefs and interest. The results of the current study will give science museums (e.g., content specialists and exhibition developers) a better understanding of how to trigger the interest of a diverse group of adults in a specific wicked problem, that is personalized medicine.

We studied people's interest in personalized medicine to illustrate the methodology described above. This topic will be part of an exhibition about scientific innovations in healthcare that has been developed and programmed by NEMO Science Museum in 2022–2023. Personalized medicine is an umbrella term covering medical models (e.g., Precision medicine and P4 medicine) in which prevention, diagnosis and treatment are aligned with patients' specific needs (Pokorska-Bocci et al., 2014). The aim is to treat patients earlier and select therapies that are accurate and effective, aligned with the patient's individual profile (Pokorska-Bocci et al., 2014; Budin-Ljøsne and Harris, 2016). To that end, it uses genetic, clinical, environmental and lifestyle information about the patient. Personalized medicine is a social issue that matters to all citizens in society. Sooner or later everyone will have to deal with health issues, and changes in health care will impact the whole society.

1.1. Research questions

1. What background variables, including socioeconomic background, are predictors of participants' interest in personalized medicine? (RQ-1).
2. Which interest dimensions best predict participants' interest in personalized medicine? (RQ-2).
3. What is the central interest dimension that has the greatest impact on the overall interest in personalized medicine? (RQ-3).

1.2. Current studies

In order to answer the research questions, we used a mixed methods approach. First, groups of adults from a low SES participated in focus groups. This sample was chosen to make sure the later developed survey would be suitable for a broad audience, which was needed to answer RQ-1. The developed survey was distributed to a broad sample and was used to answer the three research questions. Different analyses strategies were used to answer the research questions, with RQ-1 and RQ-2 being answered using regression analyses and RQ-3 being answered using a psychometric network approach.

2. Materials and methods

2.1. Focus groups

The focus groups served as a first study to explore how to survey a broad audience, including adults who do not naturally visit science museums, about their interest in personalized medicine. A focus group is "a carefully planned discussion designed to obtain perceptions on a defined area of interest in a permissive, non-threatening environment" (Krueger, 1994). This qualitative research method can offer insight into sources of complex behaviors and motivations. Because participants question each other and explain their own point of view to others, it yields more than separate individual interviews (Evers, 2015). The focus group allows the researcher to study the ways in which individuals collectively understand a phenomenon and construct meaning around it (Bryman, 2016, p. 502).

The sessions were designed to invite adults of low SES to engage in conversation about personalized medicine. Personalized medicine relates to several complex issues. Through community conversation gatherings in which experts in the field or community members were asked to share their concerns around personalized medicine, the Boston Museum of Science and Tufts Clinical and Translational Science Institute (2021) identified common themes and areas of focus. We used these themes as a starting point to design the focus groups, in which we adhered to the structure of P4 medicine: Predictive, preventive, personalized and participatory (Hood, 2008).

2.1.1. Participants

Participants with lower SES were recruited through an external agency[1] selecting adults with an educational level of secondary vocational education or below and a gross annual income below modal in three age ranges. The participants did not know in advance what topic the study was about. A total of 24 participants signed up, eighth for each age group. A total of 18 participants showed up*, consented to participate in the study and completed the focus group. [*Note that more than half of the 18–30 year olds did not show up, while the 50+ group had one participant too many]. In the final sample the average age was 50 years (SD = 16). Group 1: $N = 3$; Age range 18–30; 1 male, 2 female; 1 secondary education, 2 vocational education. Group 2: $N = 6$; Age range 30–50; 3 males, 3 females; 1 primary education, 2 secondary education, 3 vocational education. Group 3: $N = 9$; Age range 50 and older; 5 male, 4 females; 5 secondary education, 4 vocational education.

2.1.2. Procedure

Prior to the session, participants received an information letter and signed a consent form confirming that they (1) were 16 years of age or older, (2) had read and understand the information, (3) agreed to participate in the study and to the use of the obtained data, (4) reserve the right to withdraw this consent without giving any reason, and (5) reserve the right to stop participating in the study at any time. The focus group had an established structure, which included five parts: introduction round, introduction to the topic of personalized medicine, small-group discussion using a worksheet, group discussion using statements, and brainstorming on exhibition ideas. Two facilitators were present during the sessions: a scientist-practitioner who guided most of the session and conversations and a student who took care of the audio recordings. The focus groups lasted 2 h. Afterward, participants received 20 euros from the recruitment agency.

2.1.3. Materials

The focus group consisted mainly of verbal activities. To give the physically minded participants a pleasant start we began the session with a hands-on icebreaker activity (Broerse et al., 2014). Using a small bag with Lego bricks, participants were asked to build a duck. Some participants finished quickly; others found the task difficult. Then each participant introduced themselves and told a little anecdote about a duck. Although everyone had been given the same building blocks, different variations of ducks emerged—making a parallel with the purpose of the focus group: the conversations today are not about who makes the best or smartest comments, we are interested in all your ideas (Broerse et al., 2014).

The topic of personalized medicine was introduced using the example of asthma (UC San Francisco (UCSF), 2015). Participants were presented with three situations in which a fictional protagonist had an important choice to make, related to personalized medicine (e.g., this lady is often short of breath. Someone in her family died young from lung problems. She has read that people with lung problems can participate in a heredity test. She faces an important decision: is she going to apply for a hereditary test or not? How does she make her choice?). In pairs, participants discussed the situation outlined. A worksheet stimulated them to name cognitive content (what questions come to mind?), affective involvement (what emotions come to mind?) and relevant behaviors (what actions do you take?). To stimulate discussion, the groups changed composition before a new situation was introduced. After a short break, participants discussed in a plenary session three statements related to personalized medicine (e.g., The responsibility for decisions about healthcare lies with the doctor, not the patient). As a concluding activity, participants were asked what they would like to see or experience as a visitor to a scientific innovations in healthcare exhibition.

2.1.4. Analysis strategy

The focus group discussions were recorded and transcribed afterward. A qualitative analysis was performed by directive content analysis (Hsieh and Shannon, 2005) where the participants' statements were categorized into the six interest dimensions (Rotgans, 2015; Budin-Ljøsne and Harris, 2016; Sachisthal et al., 2019): Knowledge, behavior, emotion, self-efficacy, personal value, and general value. 15–20% of the data was double-coded, the inter-observer reliability was found to be "moderate" (Landis and Koch, 1977): percentage agreement = 82, and kappa = 0.53.

2.2. Online survey

2.2.1. Participants

Participants with lower and higher SES were recruited through an external agency (see text footnote 1) selecting adults with an educational

1 https://norstatgroup.com/

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level of secondary vocational education or below and a gross annual income below modal and adults with an educational level of higher vocational education or higher and a gross annual income above modal. The participants did not know in advance what topic the study was about. A total of 518 participants signed up of which 360 consented to participate in the study and completed the survey to the end. A total of 19 participants were excluded from analysis, 11 for providing repetitive answers, 5 for completing the survey too quickly (< 5 min), and 3 for whom both applied. In the final sample ($N = 341$), the mean age was 49.81 years ($SD = 15.61$). A total of 180 participants identified themselves as male, 157 as female and 4 as other/ I'd rather not say. The educational level (and SES) was low for 173 participants (78 Secondary education, 95 Vocational education) and high for 168 participants (108 Bachelor, 60 Graduate).

2.2.2. Procedure

Participants completed the online survey at home. After actively consenting to participate in the study (see section 2.1.2), participants were first asked to provide information on background measurements (e.g., age, gender, and zip code). This was followed by a short animation (2 min) to introduce the topic of personalized medicine. Then the questions on the 6 subtopics were offered. The total duration of participation was 15 min. After completing the survey, participants received 5 euros from the recruitment agency. Participants cannot be traced from the background data.

2.2.3. Materials

Based on results of the focus groups wicked problem questionnaires were constructed consisting of five subtopics related to personalized medicine: (1) Future health, (2) Adapt lifestyle to stay healthy, (3) Having a say in medical decisions, (4) Share medical data to improve healthcare, (5) Participate in scientific research to improve healthcare. As a sixth subtopic, the working title of the scientific innovations in healthcare exhibition was added: (6) How do I live to be 200?. For each subtopic participants answered 7 items on a 5-point Likert scale. Interest in a subtopic was asked both globally (e.g., I find participation in medical decisions an interesting topic, henceforth, global interest) and focused on the six interest dimensions (e.g., I experience a lot of emotions when thinking about my responsibility for medical decisions). A reliability analysis showed that the questionnaires were internally consistent for all 6 subtopics, with Cronbach's alpha scores between 0.759 and 0.815. In addition, participants were asked two open-ended questions about what they would like to see in a scientific innovations in healthcare exhibition.

The online survey also included questions about participant's age, gender and educational level, and five more background variables (also see Table 1):

TABLE 1 Factors and covariates, describing eight background variables.

			Total	Lower SES	Higher SES
Ag		M (SD)	49.81 (15.61)	52.50 (15.27)	47.04 (15.51)
Ge	Male	n (%)	180 (53)	80 (46)	100 (60)
	Female	n (%)	157 (46)	90 (52)	67 (40)
	Other	n (%)	4 (1)	3 (2)	1 (1)
Ed	Low	n (%)	173 (51)	173 (100)	0 (0)
	High	n (%)	168 (49)	0 (0)	168 (100)
Se		M (SD)	57.71 (19.04)	50.87 (18.27)	64.76 (17.19)
Ur		M (SD)	2.09[a,b] (1.83)	1.75 [a,b] (1.37)	2.43 [a,b] (2.15)
In		M (SD)	3.38 (1.36)	3.72 (1.32)	3.02 (1.31)
Af		n (%)	107 [a] (31)	64 [a] (37)	43 (26)
He		M (SD)	2.29 (0.84)	2.62 (0.89)	1.95 (0.62)

Total number (n) and percentages (%) of participants' gender, affinity for the health sector and educational level are presented, and average values (M) and standard deviations (SD) of the other background variables. Ag, age; Ge, gender; Ed, educational level; Se, self-reported socioeconomic status; Ur, degree of urbanization, the average amount of addresses per km^2 of participants' residential area; In, individual science interest; Af, affinity for the health sector; He, general health. Total, participants in final sample ($n = 341$); Lower SES, participants with an educational level of vocational education or below and a gross annual income below modal ($n = 173$); Higher SES, participants with an educational level of higher vocational education or higher and a gross annual income above modal ($n = 168$). [a]Data points were missing for urbanization and affinity for the health sector. Therefore urbanization $n_{Total} = 336$, $n_{LowerSES} = 170$, and $n_{HighSES} = 166$ and affinity for the health sector $n_{Total} = 340$ and $n_{LowerSES} = 172$. [b]Numbers must be multiplied by a thousand.

2.2.3.1. Self-reported socioeconomic status

On a scale of 1 (little money and/or education) to 10 (a lot of money and/or education), participants indicated their socioeconomic background (MacArthur Scale of Subjective Social Status; Adler et al., 2000). Self-reported SES (range 1–10) was used in analysis.

2.2.3.2. Urbanization

A measure of the concentration of human activities based on address density (Dulk et al., 1992), with five categories (low: <500 addresses/km^2; moderate low: 500–1,000 addresses/km^2; medium: 1,000–1,500 addresses/km^2; moderate high: 1,500–2,500 addresses/km^2; high: > 2,500 addresses/km^2). Participants' average address densities (AOD) were retrieved using the zip code digits of their residential areas (CBS, 2020) and were used in analyses.

2.2.3.3. Individual science interest

Participants' individual science interest (the questions were not topic specific) was assessed by three 5-point Likert-scale questions ($\alpha = 0.66$), relating to the frequency (e.g., 1 = weekly to 5 = never) with which participants read (online) science-related newspaper articles, visited science museums and listened to or watched science shows on radio, television or the internet. Average interest in science (range 1–5) was used in analyses.

2.2.3.4. Affinity for the health sector

Out of 10 sectors, participants were asked to choose the sector with which they have the most affinity. Affinity for the Health sector (dichotomous variable) was used in analyses.

2.2.3.5. General health

On a scale of 1 (good) to 5 (bad), participants indicated their general health. Self-reported health (range 1–5) was used in analysis.

2.2.4. Analysis strategy

To study what background variables are predicting participants' interest in the personalized medicine related subtopics and the exhibition's working title (RQ-1), a MANCOVA will be performed with the average interest in the six subtopics as dependent variables, and the eight background variables as factors and covariates.

To study which interest dimensions best predict participants' global interest in personalized medicine related subtopics and the exhibition's working title (RQ-2), six Backward regressions will be performed with global interest in a subtopic as a dependent variable and the six interest dimensions of a subtopic as predictors.

To infer the central interest dimensions of personalized medicine related subtopics (RQ-3), a psychometric network approach was used (*cf.*, Sachisthal et al., 2019). In psychometric networks the included measures (i.e., the items) are represented by so-called *nodes*, and their relations are represented by *edges*, which show direct connections between nodes, after controlling for all other nodes within the network (i.e., partial correlations; Epskamp et al., 2012; Schmittmann et al., 2013). Each questionnaire item on personalized medicine is represented by a node, meaning that the network model includes 30 nodes in total, based on six interest dimensions across five subtopics. We did not include the sixth subtopic. How do I live to be 200, because this subtopic was formulated from the perspective of the exhibition instead of interest in personalized medicine. To estimate the network, the *estimateNetworks* function embedded within the *R*-package *bootnet* was used (Epskamp et al., 2012). *Mgm* (mixed graphical modeling; Haslbeck and Waldorp, 2020) was used as the default to estimate the network given that it has been shown to discover true edges when the sample size is small (Isvoranu and Epskamp, 2021). Mgm can be used when variables differ in scale (i.e., binary and continuous data; Haslbeck and Waldorp, 2020). Edges are estimated using general linear models that are penalized on a node-wise basis. This is done by firstly predicting each node by all other nodes using a regularized general linear regression. In the second step, all estimated regression weights are then combined and averaged into the resulting network model. Model selection was done based on cross-validation (CV) prediction accuracy, as this form of model selection performed best in small sample sizes when the goal was to discover true edges (Isvoranu and Epskamp, 2021). A total of 10 cross-validation folds were used (Isvoranu and Epskamp, 2021).

Two network characteristics of the resulting network were investigated: First, we investigated whether communities (i.e., clusters) of nodes formed within the network. This was done using the walktrap algorithm (Pons and Latapy, 2006) which is embedded within the *igraph* package (Csardi and Nepusz, 2006). Communities are groups of nodes that are strongly interconnected. Secondly, we investigated node centrality within the network. More specifically, we determined the strength centrality (i.e., the direct influence one node has on other directly connected nodes), which is the most stable measure of node centrality (Epskamp et al., 2018; Isvoranu and Epskamp, 2021). Strength centrality is computed by summing up the absolute values of edges a given node has (Opsahl et al., 2010). The function *centralotyPlot* included in the *R*-package Qgraph was used to plot centrality (Epskamp et al., 2012).

Lastly, we tested the stability and accuracy of the network and node centrality using bootstrap and edge difference tests implemented in the *R-package bootnet* (Epskamp et al., 2018). In the context of psychometric networks, accuracy refers to the degree to which the network structure stays the same given sampling variation. The stability of node centrality refers to whether the interpretation of node centrality (i.e., which node is the most central?) stays the same even with less observations. Testing the stability and accuracy of the network and centrality is of importance given the often rather small sample sizes used to estimate psychometric networks. We followed the three steps outlined by Epskamp et al. (2018) to determine the stability and accuracy of the network: (1) edge-weight accuracy is determined based on bootstrapped confidence intervals; (2) stability of node centrality is determined based on centrality of networks estimated in parts of the observations; and (3) testing whether edges (centrality of nodes) differ significantly from other edges (nodes) using bootstrapped difference tests. Please refer to the Supplementary Material for a more thorough description of the analyses done.

3. Results

3.1. Focus groups

The conversations participants had during the three focus groups are summarized by interest dimension. Only if there were clear differences between the age groups this was indicated for the relevant dimension.

3.1.1. Knowledge

Most participants did not have much prior knowledge of the topic of personalized medicine. However, the topic did prompt many questions for all ages. These were about the example of asthma, how scientific research works and data privacy. In addition, participants were curious about technical innovations. They suggested making the technology of the future visible in the new exhibition on health care. This proposal appeared from all age groups.

3.1.2. Behavior

Two types of behavior were discussed by participants in response to the questions presented. One type was about actions to learn more about a subtopic. When gathering information, the older generation (50+) would consult their inner circle (loved ones/family) and all participants would consult the Internet and a doctor for information about a disease or for making an important medical choice. The other type of behavior was about changing lifestyle where the conversation was often about life choices. Whereas the younger generation (18–50) were not so quick to give up an “unhealthy” lifestyle, the older generation (50+) was willing to do so. Following this, the participants proposed a similar exhibition, in which the consequences of certain life choices would become visible.

3.1.3. Emotions

The topic of personalized medicine evoked both negative and positive emotions among the participants, although negative emotions such as fear, helplessness and stress dominated. These negative emotions were mentioned when the protagonist's medical situation was discussed, but also when it came to insecurity of medical data. This was true for all three age groups.

3.1.4. Self-efficacy

This was about confidence in one's own role. Participants were able to reflect on the topic of personalized medicine. Sometimes the conversation was somewhat uncertain at the beginning but this disappeared as the focus group progressed. On the subtopic of medical decisions, many participants agreed: a patient should have a say in medical decisions, but the physician has the responsibility to properly assess a patient's ability to do so. Participants were also good at indicating whether they themselves needed some form of support in making medical decisions.

3.1.5. Personal value

The personal value examples mentioned by participants dealt with themes such as self-determination, knowing where one stands, growing old healthily, carefree living, quality of life, data security and privacy. It turned out that a majority of the participants wanted to know as much as possible about his/her health in the future, in the interest of preventing disease and making the best choices regarding a possible desire for children. In this regard, a difference in age was seen, however. The younger generation (18–50) gave more value to carefree living while the oldest age group (50+) gave more value to knowing where one stands and growing old healthily.

3.1.6. General value

The general value of the topic of personalized medicine was seen by participants primarily in subtopics such as privacy and data security and mental health. The possible insecurity of medical data was discussed and what consequences this might have in terms of job security or insurance. The younger generation (18–30) also expressed a need for understanding from society about invisible mental health issues, among others. The older generation (50+) responded with a need for understanding from society about other medical conditions such as coughing in public.

3.2. Online survey

3.2.1. Descriptions of participants' background variables

3.2.1.1. Background variables

Five of the eight background variables are described below (see also Table 1), age, gender and educational level are described in section 2.2.1. *Self-reported SES.* On a scale of 1 (low) to 10 (high), participants rated their social economic status (SES) slightly above the average of 5.5 ($M = 5.771$, $SD = 1.904$). *Urbanization.* Participants' average neighborhood address density (AOD) was 2090 (SD = 1830), indicating that participants' residential area is on average highly urban. *General science interest*. On a scale of 1 (weekly) to 5 (never), participants were not frequently seeking scientific information through the media ($M = 3.38$, $SD = 1.36$). Two-thirds (67%) of the participants sometimes (weekly to annually) watch or listen to a science program on TV/radio or the Internet. More than half of the participants (57%) never visit science museums and half of the participants (50%) never read the science supplement of an (internet) newspaper. *Affinity for the health sector.* One-third of participants (31%) indicated an affinity for the Health and Wellness sector when asked to choose from 10 sectors. *General health.* Two-thirds (67%) of participants rated their health as (very) good. On a scale of 1 (good) to 5 (bad), participants rated their health below the average of 3 ($M = 2.29$, $SD = 0.84$).

3.2.1.2. Lower socioeconomic status versus higher socioeconomic status

Participants with lower SES ($N = 173$) were almost 3 years older and rated their socioeconomic background 15 points lower (Age, $M = 52.50$, $SD = 15.28$; Self-reported SES, $M = 50.87$, $SD = 18.27$) than participants with higher SES ($N = 168$; Age, $M = 47.04$, $SD = 15.51$; Self-reported SES, $M = 64.76$, $SD = 17.19$.). The percentual gender distribution (male; female; other) differed between the lower (46; 52; 2) and higher (60; 40; 1) SES groups. Science information was less often read, visited, watched or listened to in the lower ($M = 3.72$, $SD = 1.32$) than in the higher ($M = 3.02$, $SD = 1.31$) SES group. While the affinity for the health sector was higher in the lower SES group (37%) than the higher SES group (25%). Participants with lower SES rated their health less often (40%) as (very) good than participants with higher SES (60%).

3.2.1.3. Correlations between background variables

Spearman's rho shows a medium to strong correlation (rho = −0.403, $p < 0.001$) between participants' educational level and general health: higher education and better health are related. Spearman's rho shows a medium to strong correlation between participants' educational level and self-rated SES (rho = 0.368, $p < 0.001$): higher education and higher socioeconomic background are related. Spearman's rho shows a weak to medium correlation between participants' educational level and individual science interest (rho = −0.282, $p < 0.001$): higher education and frequently seeking scientific information through the media are related. Spearman's rho shows a medium to strong correlation between participants' general health and self-rated SES (rho = −0.318, $p < 0.001$): better health and higher socioeconomic background are related. Spearman's rho shows a weak to medium correlation between participants' health and age (0.200, $p < 0.001$): better health and younger age are related.

3.2.2. Descriptions of participants' interest in personalized medicine

On average, participants ($N = 341$) were interested in the five personalized medicine related subtopics: Future health ($M = 3.744$, $SD = 0.572$), Adapt lifestyle to stay healthy ($M = 3.748$, $SD = 0.557$), Having a say in medical decisions ($M = 3.710$, $SD = 0.603$), Share medical data to improve healthcare ($M = 3.737$, $SD = 0.586$) and Participate in scientific research to improve healthcare ($M = 3.631$, $SD = 0.597$). Participants had no interest in the exhibition's working title How do I live to be 200? ($M = 2.747$, $SD = 0.836$). Their interest in this subtopic was significantly lower than the five personalized medicine related subtopics [$F(5, 1700) = 252.125$, $p < 0.001$, $eta^2 = 0.426$]. See Table 2.

3.2.3. What background variables, including socioeconomic background, are predicting participants' interest in personalized medicine? (RQ-1)

To study what background variables are predicting participants' interest in personalized medicine related subtopics and the exhibition's working title, a MANCOVA was performed with the average interest in the six subtopics as dependent variables, and the eight background variables as factors and covariates. Because of violation of the covariance matrices Pillai's Trace statistics were reported.

Using Pillai's trace, there were non-significant effects of urbanization, educational level and self-reported SES and significant effects of age [$V = 0.057$, $F(6, 315) = 3.199$, $p < 0.005$, $eta^2 = 0.057$], gender [$V = 0.088$, $F(6, 315) = 5.086$, $p < 0.001$, $eta^2 = 0.088$], individual science interest [$V = 0.106$, $F(6, 315) = 6.208$, $p < 0.001$, $eta^2 = 0.106$], affinity for the health sector [$V = 0.040$, $F(6, 315) = 2.173$, $p < 0.05$, $eta^2 = 0.040$] and general health [$V = 0.047$, $F(6, 315) = 2.601$, $p < 0.05$, $eta^2 = 0.047$] on participant's average interest in the six subtopics.

However, separate univariate ANOVAs on the outcome variables revealed non-significant effects of the five background variables on some subtopics (also see Figure 1).

TABLE 2 Participants' interest in personalized medicine.

	GI	K	B	E	S	P	G	Total-i
	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)
FH	4.13 (0.96)	2.87 (0.84)	4.08 (0.89)	2.87 (1.05)	4.04 (0.78)	4.07 (0.82)	4.15 (0.81)	3.74 (0.57)
AL	4.08 (0.81)	3.50 (0.87)	3.76 (0.86)	2.86 (1.02)	4.08 (0.76)	4.00 (0.81)	3.97 (0.90)	3.75 (0.56)
SM	4.26 (0.84)	2.93 (1.00)	3.86 (0.89)	2.92 (1.09)	4.01 (0.83)	4.10 (0.85)	3.89 (0.88)	3.71 (0.60)
SD	4.05 (0.88)	3.00 (1.00)	4.00 (0.89)	2.74 (1.07)	4.19 (0.78)	4.13 (0.89)	4.05 (0.88)	3.74 (0.59)
PR	4.09 (0.91)	2.89 (1.06)	4.00 (0.88)	2.67 (1.03)	4.03 (0.80)	3.76 (0.96)	3.99 (0.87)	3.63 (0.60)
HL*	2.80 (1.34)	2.02 (0.99)	3.13 (1.37)	2.62 (1.16)	3.33 (1.16)	2.67 (1.22)	2.65 (1.24)	2.75 (0.84)
Total-s	3.90 (0.62)	2.87 (0.67)	3.80 (0.66)	2.78 (0.84)	3.95 (0.60)	3.79 (0.56)	3.78 (0.65)	

Mean values (M) and standard deviations (SD) of participants' interest in personalized medicine related subtopics and the exhibition's working title are presented ($N = 341$). FH, future health; AL, adapt lifestyle to stay healthy; SM, having a say in medical decisions; SD, share medical data to improve healthcare; PR, participate in scientific research to improve healthcare; HL, how do I live to be 200?. Interest in a subtopic was asked globally (e.g., I find participation in medical decisions an interesting topic) and focused on the six interest dimensions (e.g., I experience a lot of emotions when thinking about my responsibility for medical decisions). GI, global interest in a subtopic; K, knowledge; B, behavior; E, emotion; S, self-efficacy; P, personal value; G, general value; Total-i, the mean value of all 7 items (GI through G); Total-s, the mean value of all 6 subtopics (FH through HL). The exhibition related subtopic is marked with an asterisk.

3.2.3.1. Age

Older participants showed more interest in the subtopics Adapt lifestyle to stay healthy, $F(1, 320) = 4.376$, $p < 0.05$, $eta^2 = 0.013$, having a say in medical decisions, $F(1, 320) = 8.660$, $p < 0.01$, $eta^2 = 0.026$ and share medical data to improve healthcare, $F(1, 320) = 5.777$, $p < 0.05$, $eta^2 = 0.018$. than younger participants. However, younger participants showed more interest in the subtopic how do I live to be 200? than older participants, $F(1, 320) = 4.218$, $p < 0.05$, $eta\hat{}2 = 0.013$.

3.2.3.2. Gender

Females showed more interest in the subtopics Adapt lifestyle to stay healthy, $F(1, 320) = 11.480$, $p < 001$, $eta\hat{}2 = 0.035$ and having a say in medical decisions, $F(1, 320) = 6.079$, $p < 0.05$, $eta\hat{}2 = 0.019$ than males.

3.2.3.3. General science interest

Participants who accessed scientific information more frequently were more interested in the subtopics future health, $F(1, 320) = 18.517$, $p < 0.001$, $eta\hat{}2 = 0.055$, adapt lifestyle to stay healthy, $F(1, 320) = 9.051$, $p < 0.005$, $eta\hat{}2 = 0.028$, having a say in medical decisions, $F(1, 320) = 32.305$, $p < 0.001$, $eta\hat{}2 = 0.092$, share medical data to improve healthcare, $F(1, 320) = 19.804$, $p < 0.001$, $eta\hat{}2 = 0.058$, participate in scientific research to improve healthcare, $F(1, 320) = 23.323$, $p < 0.001$, $eta\hat{}2 = 0.068$, and how do I live to be 200?, $F(1, 320) = 4.369$, $p < 0.05$, $eta\hat{}2 = 0.013$, than participants who did so less frequently.

3.2.3.4. Affinity for the health sector

Participants involved in the health sector showed more interest in the subtopics Having a say in medical decisions, $F(1, 320) = 5.900$, $p < 0.05$, $eta\hat{}2 = 0.018$, share medical data to improve healthcare, $F(1, 320) = 5.154$, $p < 0.05$, $eta\hat{}2 = 0.016$, and Participate in scientific research to improve healthcare, $F(1, 320) = 8.919$, $p < 0.01$, $eta\hat{}2 = 0.027$ than participants who did not have this affinity.

3.2.3.5. General health

Participants with poorer health were more interested in the subtopics future health, $F(1, 320) = 10.094$, $p < 0.005$, $eta\hat{}2 = 0.031$, having a say in medical decisions, $F(1, 320) = 10.301$, $p < 0.001$, $eta\hat{}2 = 0.031$, share medical data to improve healthcare, $F(1, 320) = 5.049$, $p < 0.05$, $eta\hat{}2 = 0.016$ and participate in scientific research to improve healthcare, $F(1, 320) = 5.864$, $p < 0.05$, $eta\hat{}2 = 0.018$ than participants with better health.

3.2.4. Which interest dimensions best predict participants' interest in personalized medicine? (RQ-2)

To study which interest dimensions best predict participants' interest in personalized medicine related subtopics and the exhibition's working title, six Backward regressions were performed with global interest in a subtopic (GI) as dependent variable and the six interest dimensions of a subtopic (K through G) as predictors (a summary of the results is presented in Table 2 and Figure 2).

3.2.4.1. Future health

Interest dimensions behavior (B) and general value (G) could significantly predict participants' global interest (GI) in Future health, $F(2, 338) = 141.533$, $p < 0.001$, $R\hat{}2 = 0.456$. Both dimensions contributed significantly and positively to this prediction, $p < 0.001$.

3.2.4.2. Adapt lifestyle to stay healthy

Interest dimensions knowledge (K), behavior (B), personal value (P) and general value (G) could significantly predict participants' global interest (GI) in Adapt lifestyle to stay healthy, $F(4, 335) = 86.566$, $p < 0.001$, $R\hat{}2 = 0.508$. All four dimensions contributed significantly and positively to this prediction, $p < 0.001$.

3.2.4.3. Having a say in medical decisions

Interest dimensions knowledge (K), behavior (B), emotion (E), self-efficacy (S), personal value (P) and general value (G) could significantly predict participants' global interest (GI) in Having a say in medical decisions, $F(6, 334) = 42.609$, $p < 0.001$, $R\hat{}2 = 0.434$. All six dimensions contributed significantly and positively to this prediction, $p < 0.05$.

3.2.4.4. Share medical data to improve healthcare

Interest dimensions knowledge (K), behavior (B) and general value (G) could significantly predict participants' global interest (GI) in Share medical data to improve healthcare, $F(3, 336) = 84.955$, $p < 0.001$, $R\hat{}2 = 0.431$. All three dimensions contributed significantly and positively to this prediction, $p < 0.001$.

3.2.4.5. Participate in scientific research to improve healthcare

Interest dimensions behavior (B), emotion (E), personal value (P) and general value (G) could significantly predict participants' global interest (GI) in Participate in scientific research to improve healthcare, $F(4, 336) = 92.957$, $p < 0.001$, $R\hat{}2 = 0.525$. Behavior, personal value and

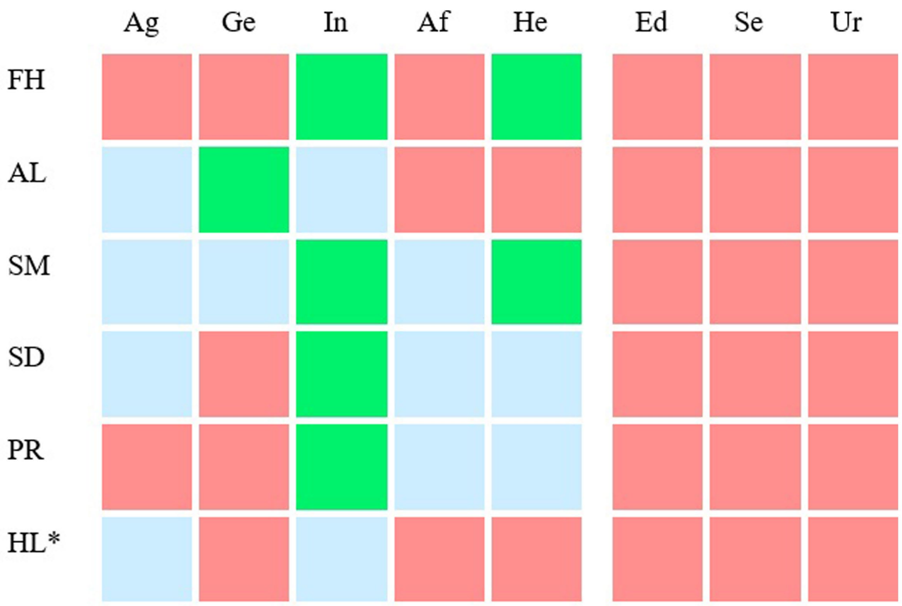

FIGURE 1
Background variables that predict participants' interest in personalized medicine related subtopics and the exhibition's working title. For six subtopics (lines 1–6) the relationship between average interest in a subtopic and eight background variables (column 1–8) was visualized. FH, future health; AL, adapt lifestyle to stay healthy; SM, having a say in medical decisions; SD, share medical data to improve healthcare; PR, participate in scientific research to improve healthcare; HL, how do I live to be 200?; Ag, age; Ge, gender; In, individual science interest; Af, affinity for the health sector; He, general health; Ed, educational level; Se, self-reported SES; Ur, urbanization of the residential area. The color of the cells depict the background variables that do (green and blue) and do not (red) significantly predict participants' average interest in a subtopic ($p<0.001$). Note that the effect sizes were small. The effect sizes (eta^2) of the green cells are between 0.1 and 0.03 and of the light blue cells between 0.03 and 0.01. The exhibition related subtopic is marked with an asterisk (line 6).

general value contributed significantly and positively to this prediction, $p < 0.001$.

3.2.4.6. How do I live to be 200?

A Backward multiple regression showed that interest dimensions knowledge (K), behavior (B), personal value (P) and general value (G) could significantly predict participants' global interest (GI) in How do I live to be 200?, $F(4, 335) = 86.566$, $p < 0.001$, $R^2 = 0.508$. Behavior, personal value and general value contributed significantly and positively to this prediction, $p < 0.001$.

3.2.4.7. Knowledge

The knowledge question predicts participants' global interest for the subtopics of adapt lifestyle to stay healthy (AL), having a say in medical decisions (SM), Share medical data to improve healthcare (SD) and How do I live to be 200? (HL).

3.2.4.8. Behavior

The behavior question predicts participants' global interest for all six subtopics (FH, AL, SM, SD, PR, and HL).

3.2.4.9. Emotion

The emotion question predicts participants' global interest only for the subtopics of Share medical data to improve healthcare (SD) and Participate in scientific research to improve healthcare (PR).

3.2.4.10. Self-efficacy

The self-efficacy question predicts participants' global interest for the subtopic of having a say in medical decisions (SM).

3.2.4.11. Personal value

The personal value question predicts participants' global interest for the subtopics of adapt lifestyle to stay healthy (AL), having a say in medical decisions (SM), participate in scientific research to improve healthcare (PR) and How do I live to be 200? (HL).

3.2.4.12. General value

The general value question predicts participants' global interest for all six subtopics (FH, AL, SM, SD, PR and HL).

3.2.5. What is the central dimension that has the greatest impact on the overall interest in personalized medicine? (RQ-3)

The estimated network model of interest in personalized medicine is displayed in Figure 3. The nodes are colored based on their community membership. Visual inspection of the network shows that both the emotion nodes and the perceived knowledge nodes form separate clusters that are relatively sparsely connected with the remaining nodes. These two interest dimensions have thus less influence on the other dimensions. The remaining nodes are relatively closely connected. Most edges are positive, with few, relatively weak negative edges. Please refer to the Supplementary Table S1 for an overview of the (partial) correlations between nodes.

3.2.5.1. Community detection

In total, four different communities were detected in the network. Communities are sets of nodes that have relatively strong connections to nodes within the set compared to nodes outside the set. Two relatively distinct communities represent the clusters of the emotion

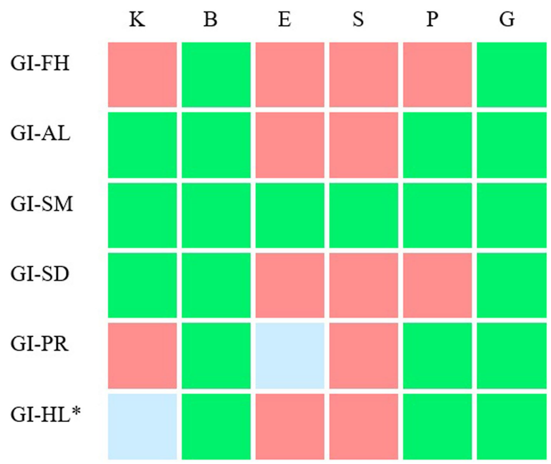

FIGURE 2
The relation between interest dimensions and participants' global interest in personalized medicine related subtopics and the exhibition's working title. For six subtopics, the relationship between participants' global interest in a subtopic (GI) and interest in the six subtopics (interest dimensions K through G) was visualized. FH, future health; AL, adapt lifestyle to stay healthy; SM, having a say in medical decisions; SD, share medical data to improve healthcare; PR, participate in scientific research to improve healthcare; HL, how do I live to be 200?. The exhibition related subtopic is marked with an asterisk. The color of the cells depict the interest dimensions that do (green and blue) and do not (red) significantly predict participants' global interest in a subtopic, when performing a Backwards multiple regression with global interest as dependent variable and the six interest dimensions as predictors. Moreover, for the green cells, these interest dimensions contribute significantly and positively to the model. For example: Behavior, emotion, personal value and general value could significantly predict participants' interest in the subtopic Participate in scientific research to improve healthcare. Behavior, personal value and public interest contributed significantly and positively to this prediction.

(green nodes) and knowledge nodes (purple nodes) across the five subtopics. The remaining interest dimension nodes were separated into two relatively closely connected communities. First, one cluster emerged including all but two nodes (i.e., knowledge and emotion) measuring interest in Future health and two nodes adapting one's lifestyle to stay healthy (i.e., self-efficacy and personal value; yellow nodes). Second, the largest community included all remaining nodes of the subtopics: Having a Say in Medical decisions, Share medical data to improve healthcare, and participate in scientific research to improve healthcare, as well as the general value node and the behavior node of the adapting one's lifestyle subtopic (red nodes).

3.2.5.2. Node centrality

A network of interacting nodes may show complex dynamics when the activity of one node (i.e., the item score) is changed. The node that has the strongest connections to other nodes is considered to have the strongest impact on other nodes in the network. For the network model of interest in personalized medicine, the node with the highest strength centrality is the node "Finding it important for society to participate in scientific research" (PR_G). This node has the strongest direct connections to other nodes in the network. Hence, this subtopic may be an interesting target for intervention. It must be noted that the stability of the result is not optimal, meaning that the centrality of some nodes is comparable (see Supplementary Material). For the most central node, only one node, "I wonder how large-scale sharing of medical data could change healthcare in the future" (SD_B), has a somewhat comparable strength. Note that both nodes have to do with understanding scientific research.

4. Discussion

4.1. Getting adults to explore difficult topics that require broad civic engagement

Wicked problems often deal with complex issues that are not easy to solve and at the same time require broad social engagement. Understanding scientific innovations is important for developing a personal perspective on these types of problems. Science centers and science museums play an important social role in engaging people in science and technology relevant to these complex social problems. As a science museum, how can a broad and diverse audience be encouraged to further develop their own perspectives on these complex issues? We design a methodology for science museums that provides starting points for this—with a focus on the development of individual interest.

4.2. The case of personalized medicine

During the concept development of an exhibition, the exhibition team (e.g., content specialists and exhibition developers) explore what aspects, questions, concepts and subtopics might be relevant to present in an exhibition on a particular topic (Neves, 2002). One way to select relevant subtopics is from the perspective of science, for example by engaging with scientists to hear what is cutting edge in their field or what are new trends in a particular area of science. Another way to select relevant subtopics is from the perspective of the potential visitor, what do visitors find interesting subtopics and what does this interest look like? In the current study we take a dynamic perspective on the development of people's individual interest by studying the structure of their interest for personalized medicine. Potential subtopics of interest were identified using a Focus group approach.

4.2.1. Conversations about personalized medicine

In order to survey a diverse adult audience's interest in the topic of personalized medicine, we first explored whether and how adults who are not likely to visit museums (e.g., adults of low SES; Falk, 2009; Dawson, 2014) think and talk about the topic. During focus group discussions, we observed what knowledge, attitudes and emotions these adults have about and in relation to personalized medicine.

The structured format of the focus groups and the introduction of personalized medicine with a concrete example (asthma) helped participants discuss a multitude of subtopics about Future health and the predictive, preventive, personalized and participatory sides of personalized medicine (Pokorska-Bocci et al., 2014). For example, questions that were discussed included: Do you want to know everything about your health in the future, would you participate in a heredity test, are you willing to change your lifestyle, would you share your healthcare data to improve healthcare, and who is responsible for making decisions about the healthcare process? The use of worksheets ensured that participants also discussed the topics from the different dimensions of interest (Knowledge, Behavior, Emotion, Self-efficacy, Personal, and General Value).

Based on the example used in the focus group (asthma), a short video was made which was used to introduce the topic of personalized

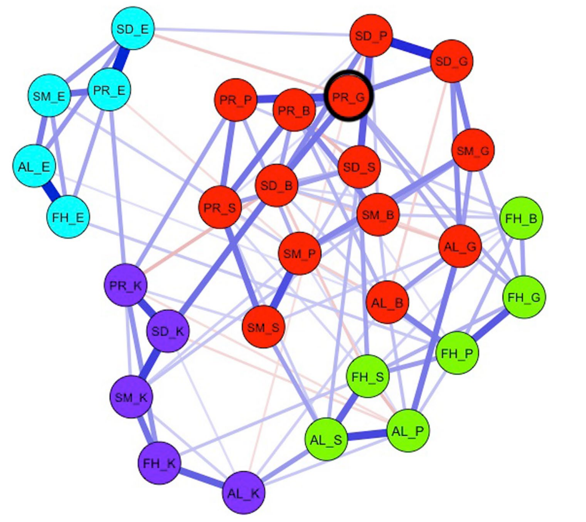

FIGURE 3
The network model of interest in personalized medicine. FH, future health; AL, adapt lifestyle to stay healthy; SM, having a say in medical decisions; SD, share medical data to improve healthcare; PR, participate in scientific research to improve healthcare; K, knowledge; B, behavior; E, emotion; S, self-efficacy; P, personal value; G, general value. The colors of the nodes correspond to detected communities within the network. Blue (red) edges represent positive (negative) relations between nodes. The most central node (PR_G) is highlighted with a black circle.

medicine to individuals filling in the survey. Moreover, insights gathered in the focus groups were used to design the questionnaires. For instance, examples mentioned by participants during the focus groups were used to design the questionnaire items.

4.2.1.1. Knowledge and behavior

Focus group participants indicated they did not have much prior knowledge about personalized medicine but had many questions. They were also curious about innovations in health care. Regarding actions related to personalized medicine, both what they did or did not do to stay healthy and what they undertook to learn about the topics were discussed. In the questionnaires, we included items questioning the degree of knowledge (Knowledge) and the degree of curiosity about the impact of innovations on health care (Behavior). Being based on a group of low SES individuals, we were interested whether knowledge and curiosity in the topic may differ for adults with higher education or for adults who have a lot to do with health care in their daily lives (educational level, self-assessed SES, general health, affinity with health sector).

4.2.1.2. Emotions and self-efficacy

Anxiety, Irritation, Sadness, Anger, Nervousness, Inability, Uncertainty, Joy, Interest, Satisfaction and Relief are examples of emotions and feelings mentioned during the interviews. Because of the multitude of different emotions that the topic of personalized medicine evoked, we decided to only include one question on the degree of experiencing emotions when thinking about the different subtopics. This contrasts with research into interest on other topics: for Climate Change the specific emotions of hope and distress were included (Sachisthal et al., 2019) whereas enjoyment was included in Science interest networks. Both one's own self-efficacy (e.g., confidence in one's own ability to make lifestyle changes) and the efficacy of others were discussed. Reduced self-efficacy was mentioned with examples such as "It also has to do with your cognitive ability, how can you get around?" and "People with a language barrier, low literacy, we need to be mindful of that within personalized medicine." Only one's own self-efficacy was included in the survey.

4.2.1.3. Personal and general value

Personal and general value examples that were mentioned in the interviews linked to the predictive, preventive, personalized and participatory sides of personalized medicine (Pokorska-Bocci et al., 2014). For example, "knowing where one stands" linked well to participating in scientific research (predictive), "growing old healthily" and "carefree living" to adapting the lifestyle to stay healthy (preventive), "data security" and "privacy" to sharing medical data to improve healthcare (personalized) and "self-determination" to having a say in medical decisions (participatory). "Quality of life" was an example that was discussed in relation to health in the future. We drew on these examples when designing the personal and general value items in the questionnaires. Therefore, these items were more content-related than, for example, the emotion or knowledge items of the questionnaires.

4.2.2. The role of background variables in interest (RQ-1)

To design exhibitions that are accessible to a broad adult audience, it is important to know the diversity of interest in the subject matter in relation to background variables.

Results show that individual science interest is a good predictor of interest in personalized medicine. Participants who more frequently sought scientific information through the media were more interested in personalized medicine than participants who did not. This was true for all six subtopics (including the exhibition working title), although the effect sizes for some subtopics were small. The effects of science interest were greatest for the personalized medicine subtopics of having a say in medical decisions, sharing medical data, and participating in scientific research.

One explanation is that people who are regularly informed about scientific developments through the media are also exposed to health care related topics, and therefore know more about these topics. Another explanation is that people who regularly search for scientific information are generically interested in scientific innovation regardless of the topic, much interest-development literature however, shows that interest is topic-specific (Tsai et al., 2008; Krapp and Prenzel, 2011; Sachisthal et al., 2019).

In addition to individual science interest, participants' health is related to their interest in the subtopics. In particular, participants with poorer health are more interested in Future health and having a say in medical decisions than participants with better health. One explanation for this may be that participants with poorer health conditions are more likely to deal with these subtopics in daily life and for example have experience with the situation where doctors do or do not involve patients in medical decisions.

Another way that participants may come into contact with the subtopics in everyday life is through their occupation, which we examined through their affinity for the health sector. However, we showed only small effects here, of which affinity with the health sector had the most effect on interest in participating in scientific research. One explanation for the small effects may be that health is a somewhat special topic, since it affects us all.

The informal science education (ISE) literature suggests that people from lower-economic groups are underrepresented in the museum (Falk, 2009; Dawson, 2014). Therefore, in the current study, we measured educational level and gross annual income (high/low SES), urbanization of the residential area, and self-reported SES.

Against our expectation, the survey shows no relationship between these background characteristics and participants' interest in the main topic of personalized medicine. All subtopics presented in the survey were of interest by both high and low SES adults (and high and low educated).

The choice of subtopics does not seem to be a limiting factor for the inclusive design of an exhibition that interests a wide audience. But it does not alter the fact that there may be other barriers that may cause adults with lower socio-economic backgrounds not to visit an exhibition about scientific innovations in healthcare in the museum after all, such as infrastructure access, literacy and community acceptance (Dawson, 2014). One possible explanation for why education level (SES) does not play a role in interest in the topics is the negative correlation between education level and health. The expectation is that people who are more educated are more interested in the topics. What contradicts this is that the lower educated in the study had poorer health and it appeared that people with poorer health are more interested in the personalized medicine subtopics.

4.2.3. Dimensions of individual interest (RQ-2)

To develop exhibitions that elicit situational interest in a more robust way, it is important to have insight into adults' individual interest in the subtopics and the nature of this interest.

Adults thought future health, Adapt lifestyle to stay healthy, having a say in medical decisions, Share medical data to improve healthcare and participate in scientific research to improve healthcare were all interesting aspects of personalized medicine. The nature of the interest in all these subtopics was in the general value people saw and in the curiosity about how innovations will impact healthcare (behavior).

General value was also discussed during the focus groups, for example in relation to the subtopic Share medical data to improve healthcare: "But then, who is allowed to see the data? If the boss is allowed to see it, he might start scratching his head as to whether he wants to employ that person. The naturalness disappears, because the boss or employer might see a person [who is genetically predisposed to a certain disease] that [the company] will have to take into account in the future."

For three subtopics (adapt lifestyle to stay healthy, having a say in medical decisions, and participate in scientific research to improve healthcare), personal value was also related with the interest in the subtopic. Note, that people with poorer health were more interested in the topic of personalized medicine, likely to the importance of the topics to their personal life (i.e., personal value).

In applying the insights to museum practice, it is not that we propose to create programs that only present the general value of scientific innovations in healthcare, or programs that only deal with the potential impact of innovations for the future. Our perspective on interest development is a dynamic one, where we aim to establish positive feedback loops between the different interest dimensions. Therefore, it is important to understand the connections between the different dimensions, which can be done through network analysis.

4.2.4. The interplay between dimensions of individual interest (RQ-3)

We constructed a psychometric network model of interest for personalized medicine by considering interest as a dynamic construct with multiple dimensions (knowledge, behavior, emotion, self-efficacy, personal value and general value). The resulting network shows the interplay between all dimensions for all subtopics. The central node in the network has the strongest direct relationship with the rest of the network and is therefore an interesting entry point to get people generally interested in the main topic. In contrast, the nodes that are more separate from the network can be expected not to contribute to the development of individual interest. Hence, we were able to explore what is the most promising way to generate individual interest for personalized medicine.

For personalized medicine, the central node turned out to be *Finding it important for society to participate in scientific research*. Offering this specific perspective in an exhibition, in combination with other perspectives and subtopics, could play a role in stimulating a more stable, individual interest in the topic of personalized medicine. Centrality indices of other nodes need to be taken with some care since the stability results are not optimal. This result is in concert with findings from the focus groups. Focus group participants felt it was important for society (i.e., general value) to participate in scientific research because by doing so, they help other people and contribute to improving treatments in the future and hopefully reduce costs for society: "If a good medicine is found, you want to contribute to that, it can also enrich your life.," "I think it is important that everyone is taken seriously, everyone counts," "It makes me feel good to participate." Participants also expressed their interest in scientific research, particularly in how it works and what it means to participate: "Who is leading the research?," "Is the research meaningful?," "How long would it take?," "And then what happens to my data?"

In contrast, in the network emotion and knowledge as dimensions of interest appeared to have little or no connection with the other interest dimensions. The fact that the knowledge questions of all subtopics together form a cluster means that this knowledge is domain-general (within the domain of personalized medicine) and that the level of knowledge is not directly related to participants' interest in the topic. The same is true for emotions. Participants did report experiencing emotions when thinking about the subtopics, but the extent to which they did so was not directly related to their interest. Therefore, showing the emotional dimension of the topic is not expected to facilitate a more stable interest.

Examples of negative emotions expressed by focus group participants when they imagined themselves in the role of the protagonist were: "I would feel nervous, because you do not know what to expect," "Uncertainty, you do not know what such an examination looks like," "Sadness, because your body is letting you down," "Fear, that you cannot breathe properly," "It gives me an oppressive feeling, when decisions are made for you." Examples of positive emotions were: "Relief, when the result of a hereditary test is good," "Happy, when you can help other people by participating in research."

4.3. A dynamic perspective on interest in the museum context

The aim of the current study was to develop a methodology for science museums to identify topic-specific leads to increase engagement of a diverse population. The methodology consisted of 7 steps. Step 1. Selecting subtopics that are relevant to a main topic. Step 2. Translating these subtopics into a concrete context. Step 3. Testing whether the selected subtopics and context prompted a conversation. Step 4. Analyzing the focus group discussions for the 6 dimensions of interest. Step 5. Based on previous steps, constructing a survey for adults with an important background variety (such as, age, gender, education, SES, local neighborhood, interest in science, affinity with the health sector and perceived health,). Step 6. Performing a network analysis to identify the most influential dimensions for engaging in the main topic (*cf.* Dalege et al., 2016; Sachisthal et al., 2019). Step 7: Work with the exhibition team to discuss how research findings can be translated into the science museum context, how results may or may not be interpreted.

The dynamic perspective on interest development advocates initiating a feedback loop between different dimensions of engagement with a topic. Whereas school-based learning may focus more on topic knowledge and value for society, outside school topics may take on more personal value and an affective dimension. Learning outside school is therefore important for the development of an individual interest in a topic. In science centers, for example, a lot of attention is usually paid to playful, enjoyable interactions. That is, associations are made between the knowledge and affective dimensions of topics. Moreover, visits that take place in a family context, which is a context where personal value may be better recognized. However, family visits to a science museum is not for all families part of their practices. Adapting exhibitions and advertising for them to relevant dimensions of interest of a wide audience is one step to facilitate interest development.

4.4. Limitations and future studies

This study was designed to represent a wide audience by selecting participants with different SES and educational levels. Nevertheless, it must be noted that all participants wanted to participate in research in the first place. Results on node centrality in the network model of personalized medicine show that understanding the importance of scientific research is central. At first glance, this result might seem trivial. However, it should be noted that the result concerns *individual variation* in understanding the importance of scientific research, and not a high average value. It is not directly clear that the selection of participants affected this variation within the group of participants who were all recruited through the same procedure. In the case of science interest, for example, boys and girls had significantly different average values of several dimensions of science interest, but the network structure and thus the centrality of nodes, did not differ significantly (Sachisthal et al., 2019).

4.4.1. Performing network analysis

Museums can download free software (JASP), which includes options to perform network analyses (Van Doorn et al., 2021). A step-by-step instruction for performing the network analysis in JASP will be written up in a blog post modeled after this blog post[2] and the interest data from the current study will be made publicly available (see Supplementary Material). This will offer the possibility to practice network analysis with real data.

2 https://jasp-stats.org/2018/03/20/perform-network-analysis-jasp/

5. Conclusion

Societies face many wicked problems, which require broad social engagement. In their role of engaging individuals in science and technology, science centers and science museums can take a central role in engaging the public with such wicked problems. Through this engagement, individuals are facilitated to develop a personal perspective on these problems. As wicked problems require broad social engagement, science museums strive to encourage a broad and diverse audience to engage with the complex issues at hand. In the current study, we present a methodology aimed at finding leads on how to design exhibitions that elicit situational interest such that visitors' engagement might contribute to the development of individual interest. This was done using personalized medicine as a case study and is based on theories of interest development. Our aim has been to develop a methodology for science museums that provides insights concerning the interests in specific topics of a broad population and thereby inspire exhibition development to put individual interest of people central in designing exhibitions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Ethics Review Board of the Faculty of Social and Behavioral Sciences, University of Amsterdam, Netherlands. The patients/participants provided their written informed consent to participate in this study.

Author contributions

RF and MR conceived the ideas and designed the study. RF supervised the data collection. RF, MS, and MR performed the statistical analysis and wrote the manuscript. All authors contributed to manuscript revision, read, and have approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Dinos and GoPros: Children's exploratory behaviors in a museum and their reflections on their learning

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Research in both laboratory and museum settings suggests that children's exploration and caregiver–child interaction relate to children's learning and engagement. Most of this work, however, takes a third-person perspective on children's exploration of a single activity or exhibit, and does not consider children's perspectives on their own exploration. In contrast, the current study recruited 6-to 10-year-olds (N=52) to wear GoPro cameras, which recorded their first-person perspectives as they explored a dinosaur exhibition in a natural history museum. During a 10-min period, children were allowed to interact with 34 different exhibits, their caregivers and families, and museum staff however they wished. Following their exploration, children were asked to reflect on their exploration while watching the video they created and to report on whether they had learned anything. Children were rated as more engaged when they explored collaboratively with their caregivers. Children were more likely to report that they learned something when they were more engaged, and when they spent more time at exhibits that presented information didactically rather than being interactive. These results suggest that static exhibits have an important role to play in fostering learning experiences in museums, potentially because such exhibits allow for more caregiver–child interaction.

KEYWORDS

museum, STEM learning, dinosaurs, exploration, informal education

Introduction

Over the last few decades, a growing body of work has focused on how exploratory behaviors, like play, serve as a foundation for learning (e.g., Rubin et al., 1983; Saracho, 1991; Pellegrini and Boyd, 1993; Lillard et al., 2013; Weisberg et al., 2016). Relations between exploration and learning have been studied both in the laboratory and in naturalistic environments, with studies on children's naturalistic behaviors often seeking to translate findings on the relation between exploration and learning from the laboratory to more real-world settings (see, e.g., Callanan and Valle, 2008; Kline, 2015; Legare et al., 2017). To improve the ecological validity of studies of children's learning from their exploration, researchers have begun to investigate the experiences that children and families have together in museum settings (e.g., Callanan, 2012; Sobel and Jipson, 2016). Museums offer children and families the opportunity to explore together, enabling researchers to study the interaction between children's exploration and the dynamics of the family structure in a more authentic way (e.g., Allen, 2004; Gutwill and Allen, 2010; Falk and Dierking, 2018).

For example, many studies conducted in informal learning environments, such as children's museums, examine the ways that children explore exhibits and how that exploration relates to their engagement with the exhibit content (e.g., Crowley et al., 2001; Fender and Crowley, 2007; Tare et al., 2011). Such studies also investigate what children might understand about their exploration through their reflections on their behaviors (e.g., Haden, 2010; Acosta et al., 2021; Marcus et al., 2021; see also McKeown and Gentilucci, 2007). However, most studies in museum settings focus on the ways in which children and their families interact at a particular exhibit or ask children to engage with a particular set of materials. Fewer studies consider how children explore large spaces within a museum, where many displays or exhibits compete for their attention. Because of this, it remains unclear how children's exploration of larger museum spaces might relate to their engagement with the educational materials, to their beliefs about whether they learn from this material, and to the social interactions with caregivers and others who could serve to guide their learning.

Further, most of the prior work on children's exploration and learning in museum settings have examined children's behaviors and interactions from a third-person perspective, and children have only been asked to reflect on their experiences from memory. To begin to address these issues, the current study examined children's exploration of a two-story dinosaur exhibition in a natural history museum (the Academy of Natural Sciences in Philadelphia). Six-to 10-year-olds wore head-mounted GoPro cameras to record their first-person perspective as they explored the exhibition. During a 10-minute period, children were allowed to interact with different exhibits, their caregivers and families, and museum staff however they wished. This way of capturing children's experiences within a museum setting provides us with a unique view of how children explore scientific information while interacting with caregivers and others.

Children's exploration in museum settings

While there are several datasets that aim to capture naturalistic first-person data from babies and children (e.g., Smith et al., 2011; Jung et al., 2018; Slone et al., 2018; Sullivan et al., 2021), our design was inspired by a study conducted at Providence Children's Museum, which also used GoPro cameras to capture children's first-person perspectives on their interactions with the exhibit elements (Sobel et al., 2022b). That study focused on how children set goals for these interactions and the circumstances under which they changed those goals or their approach to achieving those goals. One of the main findings from that study was that children tended to be more engaged by the exhibits and to stay longer when they set their own goals, rather than when they followed goals suggested by the museum. In addition, children were more likely to revise their behaviors to try to achieve their goals when they interacted collaboratively with others (usually parents), as opposed to when they were acting alone or in parallel with others.

While that study conducted a similar investigation to the one reported here, Providence Children's Museum differs in several key ways from the current museum context, allowing the current work to make novel contributions to our understanding of how children explore in museum spaces. One of the primary differences is that the Providence Children's Museum exhibition was almost entirely interactive; children engaged with hands-on activities designed to prompt spatial thinking, such as a SOMA cube or Jovo blocks. The dinosaur exhibition investigated here had a few interactive elements but was primarily designed around having visitors view artifacts and read about them on informational plaques. This fundamentally changes the type of interactions that children are able to have with the exhibition. Indeed, the fact that the dinosaur exhibition included both interactive and didactic (or static) elements allowed us to investigate how these different kinds of exhibits affected children's engagement and their interactions with their caregivers. While much work in developmental psychology suggests that children learn effectively from hands-on experiences (e.g., Schulz et al., 2007; Chi, 2009; Lapidow and Walker, 2020; Nussenbaum et al., 2020; Sobel et al., 2022a), static exhibits have different strengths and can also inspire children's engagement in museums (e.g., Peart and Kool, 1988; Tunnicliffe and Scheersoi, 2009; Dancstep et al., 2015). One important question for the current study is thus the impact that these different kinds of experiences can have.

Second, the spatial thinking exhibition at Providence Children's Museum was only about 1,000 square feet in total area, and was stanchioned off. Parents could sit at one end of the space while their children played, knowing that their children were safely confined. As a result, only 20% of children's recorded play in that study was with their parent. In contrast, the dinosaur exhibition at the Academy of Natural Sciences was about 10,000 square feet in area and was spread across two floors. Caregivers thus often stayed nearby their children at all times, given the size of the museum and the number of visitors.

Another key difference is that the exhibit at Providence Children's Museum, while focused on encouraging children's spatial thinking, did not aim to teach particular pieces of scientific information. By contrast, the dinosaur exhibition did have this goal, aiming to teach visitors about different kinds of dinosaurs, ways in which dinosaurs are similar to and different from currently living species, and the scientific process of paleontology. Additionally, the dinosaur exhibition at the Academy of Natural Sciences was geared toward a much wider range of ages than the spatial thinking exhibit at Providence Children's Museum. Practically speaking, this meant that many of the exhibits presented text and other didactic elements that required adults to interpret them for younger visitors. These differences necessitated different approaches to data coding and analysis in the current study. In particular, the current study aimed to investigate how children's interactions with the exhibit elements and with their caregivers might shape their experiences of the exhibition.

Although we did not study play behavior directly, this focus draws theoretically on the framework of *guided play*, which involves a tradeoff between adult scaffolding and child autonomy, and which is beneficial to achieving learning goals (Weisberg et al., 2013, 2016). As in studies of guided play, the current work aimed to shed light on how adult-child interaction can help or hinder children's learning and engagement. Previous museum-based studies have followed this framework and have similarly focused on the relation between parent–child interaction during children's exploration of STEM-based exhibits and their learning. To take one example, Sobel et al. (2021) asked 4-to 7-year-olds and their parents to play together at a circuit exhibit. They coded the ways in which parents and children interacted in terms of *goal setting* – who set goals for the ways in which the dyad played. Some dyads were more parent directed, in which parents set goals for the play. Others were child directed, in which parents were more hands-off and allowed children to set goals. Still others were jointly directed, in which goals were set collaboratively, or parents were more supportive of how their children set goals. This study found that parental goal setting directly related to how engaged children were with a set of circuit construction challenges that were presented to children on their own (see also Fung and Callanan, 2013; Callanan et al., 2020; Medina and Sobel, 2020). In light of this, another goal of the present study is to confirm these results in the larger, more open setting of the dinosaur exhibition, investigating whether the relation between adult goal setting and children's engagement extends to exploration across a set of exhibits, as opposed to their engagement with a single activity.

To that end, in addition to looking at the ways that adults might set goals for their children's exploration of the space, we also considered one facet of the interaction between caregivers and children in more detail, which we called *juicy moments*. This aspect of our investigation was inspired by work by Gutwill and Allen (2010), which showed that encouraging families to develop 'juicy questions' about exhibits – questions that can be answered by interacting with the exhibit – families were more likely to set goals and generate explanations related to the questions. The families in that study also spent more time at the exhibits, suggesting children were more engaged by the experience. The current study did not explicitly ask families to generate such questions; rather, the point of connection between our investigation and theirs is in considering how 'juicy' aspects of a museum visit (instantiated here a moments of particularly rich engagement or of potential learning) relate to the nature of the exhibit or to how children reflect on their experience.

Children's reflections on their exploration

How children talk about their exploration in museums reflects what they understand about their experiences and their later learning (e.g., Haden, 2010). For instance, Marcus et al. (2017) showed that when children were presented with causal information during parent–child interaction in a museum, the children talked more about that causal knowledge when they reflected on their experience, even 2 weeks after their visit. Such causal knowledge also transfers to challenges presented in the home a week after their visit (Marcus et al., 2021). Similarly, the more STEM-based talk parents generated while playing with their children at STEM-related exhibits, the more STEM-related content children generated when asked to reflect on the activity (Acosta et al., 2021). These data suggest that reflection is an important component of children's memory for and understanding of an exhibit and potentially what they learn from exploratory contexts like play.

What is not studied as much is the extent to which children make metacognitive judgments about whether they learned from their experience at the museum. Several laboratory-based studies suggest that children undergo significant development regarding the metacognitive capacity to reflect on their own learning between the ages of approximately 5 and 8 (Esbensen et al., 1997; Bartsch et al., 2003; Bemis et al., 2011, 2013; Tang and Bartsch, 2012; Sobel and Letourneau, 2015). Moreover, during this same age range, children also begin to appreciate the distinctions between learning and play and the relations between them, such as the idea that learning can occur through play (e.g., Howard et al., 2006; Letourneau and Sobel, 2020). In order to capture how children conceptualized their own learning in this exhibition, we showed children the GoPro video that they recorded of their own exploration and asked them to reflect on why they went to a particular exhibit, what they were doing and thinking about while at that exhibit, and whether they learned from their exploration (as in our prior study at the Providence Children's Museum; Sobel et al., 2022b). Our goal with these questions was to document how children reflected on their own experiences of exploration and learning, whether they believed they had learned anything from the exploration, and, if so, whether there was any aspect of their exploratory behavior that predicted their saying that they had learned something.

Finally, as noted above, one important reason to conduct museum-based investigations is to gain insight into children's behavior and social interactions in naturalistic contexts, breaking down the barrier between the laboratory and the real world. But an important difference between museum-based and lab-based studies on children's exploratory behavior is that the museum-based work reported here does not include a direct measure of learning, only children's reports of whether they thought they had learned something and the ways in which they talked about their experiences at the exhibits. Although the dinosaur exhibition that we investigated was designed to be pedagogical, different aspects of the exhibition aimed to teach different pieces of information. Because children were allowed to explore freely, not every child visited the same set of exhibits, which did not allow us to construct a measure of children's learning that would be consistent across participants. More importantly, children entered the exhibition with different amounts of knowledge about dinosaurs and paleontology; some of our participants had even visited this exhibition before. A pre-test of children's knowledge could allow us to equate for those differences, but asking children specific questions before their exploration would likely have skewed their attention to different aspects of the exhibition and changed how they explored, damaging our ability to observe truly naturalistic behavior. For those reasons, the main goal of the current investigation was not to measure what children learned *per se*, but rather their beliefs about whether they learned.

The current study

Children's engagement and learning are affected by the way in which their caregivers interact with them, particularly the extent to which caregivers let their children set goals autonomously. One major goal of the current investigation is to explore those effects in a more naturalistic set of interactions in order to clarify how these kinds of interactions can lead to beneficial outcomes. In turn, the results of this project can suggest ways to encourage these kinds of interactions in informal learning environments.

A second major goal of the current investigation is to probe more deeply how children conceptualize their own learning in a museum setting and how they reflect on their own actions during their exploration of the museum. Most of the prior work on children's scientific thinking and causal reasoning in early childhood tends to focus on children's first-order learning about novel causal systems, and does not consider children's metacognitive views of their own learning. Despite this, metacognitive reflection plays a vital role in the development of children's scientific thinking (Kuhn, 2007; Weisberg and Sobel, 2022). This project begins to explore these questions in two ways: (1) by capturing moments in children's exploration where they seemed to be having particularly rich and important experiences (juicy moments), and (2) through a post-exploration interview, in which participants were shown key moments from the video that they created on their head-mounted GoPro during their exploration and were asked to reflect on what they were doing and why.

This combination of children's first-person perspectives during their exploration of the exhibition and their post-exploration reflections allows us to probe in detail what sparks children's engagement with museum exhibits as well as what insights they might have about their own exploratory behaviors. Although the rich data set that we have collected here can allow for many different investigations into different aspects of children's experiences, the current study focuses primarily on correlates of children's engagement and on relations between their engagement and their own reports of their exploratory behaviors. These analyses can provide unique insights into the basis of science learning in museums and other informal settings.

Finally, the nature of this exhibition allowed for another facet of considering caregiver–child interaction and its relation to children's learning and engagement: the specific design of the exhibits. Some of the exhibits were static, designed primarily to be examined visually and presenting textual material to read. These exhibits didactically communicated explicit pieces of information about dinosaurs and paleontology. Other exhibits were more interactive, affording hands-on experiences and actions on the part of children and other visitors that might produce learning. Comparison of these types of exhibits, and their relation to children's reflections and what children say about whether they learned, is of interest to thinking about the pedagogy of how information is presented in museum settings.

Methods

Participants

We recruited all the participants in this study while they were inside a dinosaur exhibition of a local natural history museum. The final sample includes 52 focal children between the ages of 6 and 10 years (mean age in months = 96.08,[1] SD = 14.49), who participated together with whoever they had come to the museum with (caregivers, siblings, etc.). Three additional children were consented, but either chose not to participate in the study ($n = 1$) or ended their exploration after only a few minutes ($n = 2$). Data collection occurred between September 2019 and February 2020. We had planned to collect data from 60 children to match the sample size in Sobel et al. (2022b), but data collection was interrupted by the COVID-19 pandemic. We were unable to complete the sample when the museum reopened because the space had been reorganized to accommodate distancing requirements, so any additional observations would not have been adequately comparable to the original sample.

Our sample included 20 female and 32 male children. Of the 49 participants whose parents or guardians reported their race, there were 39 white participants, 6 Black participants, and 4 mixed-race participants. Additionally, 7 participants identified as Hispanic or Latino and 10 identified as not Hispanic or Latino; the remaining participants did not respond to this question. Parents also were asked to fill out a questionnaire reporting on other demographic factors and their views about science; more information about responses to this questionnaire can be found in the Supplementary materials.

For each participant, we identified the caregiver with whom they interacted the most in order to analyze caregiver–child interactions. Of these caregivers, 28 were female and 24 were male. Again, more information about the demographics of the sample are presented in Supplementary materials.

1 One parent did not provide their child's exact birthdate but did confirm that the child was in our age range. This child's data was not included in any analysis reported below concerning age, hence the different degrees of freedom for those analyses.

Exhibition

This study focused on children's exploration of the Dinosaur Hall exhibition at the Academy of Natural Sciences in Philadelphia. This exhibition stretches over two floors just to the right of the main entrance to the museum and is often the first place that families come after visiting the admissions desk.

For the purposes of our analyses, in consultation with curators and other museum staff, we divided the exhibition up into 34 exhibits (one participant experienced an additional special exhibit involving live chickens that was only available for that participant). Seven of the exhibits were classified as interactive, and the other 27 were classified as static. Interactive exhibits allow visitors to engage in actions that have an effect on the exhibit, such as the "Big Dig," where visitors can brush away shredded cork pieces to find replica dinosaur bones, and a treadmill that is connected to a dinosaur skeleton, so that visitors who walk on the treadmill can make the skeleton move. Static exhibits present fossils, bones, or other artifacts, and visitors can read information about dinosaurs or paleontologists from plaques. See Supplementary Table S1 for a description of all of the exhibits and their classification as static or interactive. A map of the space with thumbnail photographs of the 34 exhibits can be found on OSF.[2]

Procedure

Exploration

In this study, participants wore a head-mounted GoPro camera to record their first-person perspective as they explored the dinosaur exhibition. Children were allowed to interact however they wished with different exhibits, their caregivers and families, and museum staff. A research assistant followed each participant with a second GoPro camera (chest-mounted), recording a third-person perspective on what the participant was doing. During data collection sessions, we posted signage at the entrances to the exhibition informing museum visitors that we would be video-recording in this exhibition for research purposes, so they could choose to avoid the exhibition if they did not want to be recorded.

Participants were given 10 minutes to explore freely before proceeding to the post-exploration interview (see below). The research assistant gave the child a warning at 8 minutes that their time was almost over. We chose to end the exploration period after 10 minutes partially to match the method used in a previous study of children's museum exploration using GoPros (Sobel et al., 2022b), but also to impose some experimental control for the sake of the reflection interviews; we wanted all children to have the same amount of time exploring to reflect on in the interviews. Moreover, limiting the time spent exploring ensured that the length of the overall research session was roughly the same for all participants, thereby not affecting their experience visiting the museum differently.

All videos that parents provided permission to share are available on Databrary.[3]

2 https://osf.io/8xghm/

3 http://doi.org/10.17910/b7.854

Post-exploration interview

Following the exploration period, children engaged in an interview that was similar the one used in prior work (Sobel et al., 2022b).

The first thing that happened in this interview was that the research assistant who had followed the child during the exploration period asked them to reflect on their exploration. To do so, the research assistant used the GoPro app on an iPad to pull up the first-person footage that the participant had recorded during their exploration. She scrubbed through this footage to find key moments in the participant's visit, using the video as a reminder to the participant of the exhibits that they had visited. For each of these moments, the research assistant asked participants (1) why they chose to go to that exhibit, (2) what they were doing there, and (3) what they were thinking about. To keep the post-exploration interviews brief, participants were not asked about every exhibit that they had visited. Instead, the research assistant always asked about the first exhibit that the participant visited and then chose a few other exhibits that the research assistant judged to have included particularly interesting interactions or particularly meaningful engagement (following the same procedure described in Sobel et al., 2022b).

At the end of these reflections, the research assistant asked whether they had learned anything during their museum exploration. If the participant responded that they had, they were asked what they learned and how they learned it. If the participant responded that they had not, they were asked what they were doing and whether they could have been learning while they were engaged in whatever other activity that they named.

Children were also asked a set of questions regarding their understanding of learning (following work by Sobel and Letourneau, 2015). The results of this interview were unrelated to the analyses reported here, and these data are reported in the Supplemental materials section.

The full script for the post-exploration interview can be found on OSF.[4]

Coding

Visit metrics

Children were coded as having visited a particular exhibit if they were physically present at it or looking at it for at least 5 seconds. All exploration videos were transcribed and participant behaviors (e.g., pointing) were coded using Datavyu; these coding files are available together with participants' videos on Databrary (see footnote 3).

Child engagement

We coded how engaged each child was during the exploration period on a scale of 1 to 5, with 1 indicating no engagement and 5 indicating high engagement. Each child received a single code reflecting their overall level of engagement. Behaviors indicative of higher engagement involved the child showing clear enthusiasm for or interest in the exhibits, for example, asking questions, actively reading placards, touching or interacting with exhibits, and so on. Coders were thus instructed to pay attention to facial expressions, body language, verbal content, and the variety of exhibits that the child visited. Importantly, because children received a single score for engagement for the entire exploration period, this score did not simply reflect the amount of time spent at any particular exhibit. Rather, it aimed to holistically capture children's behavior across the entire exploration period. A team of two coders, one of whom was the second author, independently coded each video in the set. The coders met after every 5 videos to discuss and reconcile any discrepancies. Cronbach's alpha for agreement between the two coders was 0.97.

Caregiver–child interaction

A separate set of three coders, together with the second author, identified a primary caregiver for each participant and coded the child's interactions with this caregiver, again on a scale of 1 to 5. Following prior work on caregiver-child interaction in museums (e.g., Callanan et al., 2020; Medina and Sobel, 2020; Sobel et al., 2021), scores of 1 or 2 indicated that the interaction was entirely or mostly child-directed, scores of 3 indicated collaboration, and scores of 4 or 5 indicated that the interaction was mostly or entirely caregiver-directed. Each video was coded independently by two coders, who met with the second author after every 5 videos to reconcile any discrepancies. The average Cronbach's alpha for the different pairs of coders was 0.71.

Juicy moments

Because we had no direct measure of children's learning, we aimed to draw out moments of potential learning from children's exploration videos. The first author and a team of four coders developed a coding scheme to capture such "juicy moments," in which children were engaging with exhibits and/or with other individuals in such a way that indicated that they were learning something, changing their minds, or having a particularly important experience. For example, when looking at a fossilized fish, one participant said, "But really, fishes do not have bones. So that's the only fish that looks like it has bones." She was corrected by her father, who said, "No, that's not true, fishes have bones," to which she responded, "Oh!" Although these moments could be indications of engagement, this coding scheme is importantly distinct from our coding of children's overall engagement in its focus on specific moments in children's exploration and in its focus on indications of potential learning, beyond general excitement or enthusiasm. For this coding scheme, each participant was assigned to two coders who worked independently. They watched the GoPro footage that children had generated and noted the timestamp of each juicy moment, and they periodically reconciled their codes under supervision from the first author. Agreement on the final set was 99.7%.

Reflections on exploration

During the reflection interview, children were first asked why they approached that exhibit. This response was coded for whether children articulated a reason that was intrinsic (e.g., "I wanted to learn about the dinosaur," "I wanted to try the walking") or a reason that was either more descriptive or extrinsic ("Julia [sister] was over there," "Dinosaurs are big").

Children were then asked what they were doing and thinking about at the exhibit. Responses to this question were coded for whether they conveyed factual information about dinosaurs or another facet of the exhibit, beyond just an observation of what they had said or done (e.g., "That the holes that are on the tailbone were from teeth").

A subset of the data (20 videos or 38% of the sample) were coded by two undergraduate research assistants, blind to the hypotheses of the study and children's age or any other demographic information.

4 https://osf.io/8xghm/

Agreement for the coding of intrinsic vs. extrinsic reasons was 90.7%, Kappa = 0.81. Agreement for the coding of whether children provided factual information in their reflections was 92.3%, Kappa = 0.82. Disagreements were resolved through discussion. One of those coders then coded the remaining data.

"Did you learn something?"

The post-exploration interview asked children if they learned anything. Children who said "yes" were then asked what they learned. Responses to this question were coded as either referring to content (e.g., "dinosaurs can be really small") or to a process or strategy for learning (e.g., "it was cool to read all those things I did not know"). They were then asked how they learned. These responses were coded as describing learning either with respect to behaviors (e.g., "I looked inside the skulls") or with respect to mental states (e.g., "I thinked about how that's how dinosaurs grow").

Children who said "no" to the initial question of whether they had learned something were then asked what they were doing. Responses to this question were coded as either referring to behaviors (e.g., "just to look at prehistoric animals") or to mental states (e.g., "thinking about stuff"). They were then asked if they could have been learning while doing that other activity, and they could say yes or no.

Two coders initially coded 20% of the sample to check for reliability on these two sets of codes. Agreement on this subset was 90%, Kappa = 0.86. One coder then coded the rest of the sample.

Results

Children's experiences in the exhibition

Supplemental Table S1 provides descriptive information about each exhibit, including the total number of visitors and the average amount of time spent there.

Children made an average of 10 visits to exhibits during their exploration time (Range 2–27); these numbers include times when they returned to a previously visited exhibit. Children visited an average of 9 unique exhibits (Range 2–18). They made an average of 7 visits to static exhibits (Range 0–27) and 3 visits to interactive exhibits (Range 0–8).

In terms of time spent, children were actively visiting exhibits during their 10-minute exploration time (as opposed to transitioning between exhibits) for an average of 448 seconds (Range 102–808 seconds). They spent on average 215 seconds at static exhibits (Range 0–749 seconds, average proportion of total exploration time 46.4%) and 233 seconds at interactive exhibits (Range 0–619 seconds, average proportion of total exploration time 53.6%).

We identified an average of 0.73 juicy moments per exploration, with more of such moments occurring at the static exhibits ($M = 0.55$) than at the interactive exhibits ($M = 0.18$).

Child engagement during exploration

One of our primary questions for this project was to investigate what factors would relate to child engagement in the exhibition. Table 1 shows the zero-order correlations among children's engagement score and their age, as well as the relations among those variables and the time spent exploring and whether the exhibits encouraged children to have a juicy moment.

Our analyses first considered the extent to which children explored each exhibit and its relation to their engagement and to the nature of their interaction with their caregivers. There was no relation between the length of time children explored and their age, $r(49) = 0.004$, $p = 0.98$. However, older children spent more time at static exhibits, $r(49) = 0.37$, $p = 0.007$, and younger children spent more time at interactive exhibits, $r(49) = -0.40$, $p = 0.004$. Boys and girls did not differ in the overall amount of time children spent exploring, or in the amount of time they spent exploring either the static or interactive exhibits, all Mann Whitney Tests, $|z| < 0.80$, all p-values >0.42.

Children's engagement with their exploration was rated 3.94 on average (Range 2–5). Boys ($M = 3.93$) and girls ($M = 3.95$) were no different in their overall level of engagement. Children's engagement scores correlated positively with the total time children spent exploring, $r(49) = 0.55$, $p < 0.001$. That is, the more time children spent exploring, the more engaged they were judged to be. That correlation was also significant when controlling for age, $r(48) = 0.55$, $p < 0.001$. As can be seen in Table 1, the amount of time children spent at the static exhibits correlated with their engagement, and this relation held when age was controlled for, $r(48) = 0.35$, $p = 0.01$. However, the amount of time children spent at the interactive exhibits did not relate to their engagement. As can also be seen from Table 1, the juicy moments that happened at the static exhibits related to children's engagement; this correlation was also significant controlling for age and the amount of time children spent at the static exhibits, $r(46) = 0.41$, $p = 0.003$.

We next considered the relation between children's engagement and the extent to which caregivers guided their children through the exploration, as defined by the three categories of caregiver-child interaction style. Collaborative dyads ($n = 15$) spent more time exploring overall (Mean = 461.40 seconds, SD = 83.37) than caregiver-led dyads ($n = 12$, Mean = 449.66 seconds, SD = 75.25) and child-led dyads ($n = 25$, Mean = 438.20 seconds, SD = 147.71). Children in collaborative dyads were also rated as more engaged (Mean = 4.33, SD = 0.72) than children from caregiver-led (Mean = 3.75, SD = 0.45) or child-led (Mean = 3.80, SD = 0.96) dyads. Collaborative dyads also generated more juicy moments during the course of their exploration ($M = 1.14$) than either caregiver-directed ($M = 0.58$) or child-directed ($M = 0.56$) dyads. This was specifically the case for static exhibits, where collaborative dyads generated more juicy moments ($M = 1.00$) than the other two groups ($M = 0.33$ and $M = 0.40$, respectively). However, neither of these differences were statistically significant, Kruskal–Wallis $H(2) = 2.66$ and 4.25, $p = 0.27$ and 0.12.

To analyze these data together, we constructed a set of hierarchical regression models. The first model predicted children's engagement score from their age, the time spent exploring the interactive exhibits, the number of juicy moments that occurred at the interactive exhibits, and the number of static exhibits and number of interactive exhibits that children visited. These latter two variables were included to control for the fact that there were more static exhibits in the exhibition than interactive ones. This model did not explain a statistically significant amount of variance, $R^2 = 0.20$, $F(5,44) = 2.25$, $p = 0.06$. We then added caregiver-child interaction style to this model. This new model predicted a significant amount of additional variance, $\Delta R^2 = 0.13$, $F(2,42) = 3.97$, $p = 0.03$, with children in the collaborative group being more engaged than children in the child-directed group, $B = 0.37$, $p = 0.009$. We then added the time children spent only at the static exhibits, and this also predicted a significant amount of additional variance, $\Delta R^2 = 0.12$, $F(1,41) = 9.08$. Finally, we added to the model the number of juicy questions children generated at the static exhibits, which also predicted

TABLE 1 Correlations among children's engagement, age, time spent exploring, and juicy moments.

	Children's engagement (scale of 1–5)	Time exploring static exhibits	Time exploring interactive exhibits	Number of juicy moments at static exhibits	Number of juicy moments at interactive exhibits
Children's age	0.10	0.37*	−0.40*	−0.002	−0.31*
	$p = 0.47$	$p = 0.007$	$p = 0.004$	$p = 0.99$	$p = 0.03$
Children's engagement		0.36*	−0.003	0.41*	0.09
		$p = 0.008$	$p = 0.98$	$p = 0.003$	$p = 0.55$

A * indicates a statistically significant result.

a significant amount of additional variance, $\Delta R^2 = 0.06$, $F(1,40) = 4.42$, $p = 0.04$. This final model was significant overall, $R^2 = 0.51$, $F(9,40) = 4.56$ $p < 0.001$.

To summarize, this set of analyses examined what factors related to children's engagement with their exploration of the exhibit. We found that the time children spent at static exhibits and the number of juicy moments at those exhibits were most predictive of their engagement: Children who spent more time and who generated more juicy moments with their families at those exhibits were rated as more engaged.

Post-exploration reflections

Our next research question investigated how children talked about their exploration, particularly in terms of the motivation they had for their actions and the extent to which they understood the content of the exhibits. In general, children provided reflections on 2–9 exhibits (Mean = 5.00, SD = 1.67) in their post-exploration interviews.

We first considered how children described their decision to go to a particular exhibit during these reflections.[5] Overall, children stated that their reason for visiting an exhibit was intrinsic to their interests on 44% of their reflections. We analyzed these data with a Generalized Estimating Equation with a robust correlation matrix, to control for the within-subject nature of the question, assuming a binomial response. Age, caregiver-child interaction style, whether the exhibit was static or interactive, the total time children spent exploring, and the order of the reflections were the independent variables. All main effects were considered as were interactions concerning the first four variables (because there is no hypothesized reason why interactions with order of reflection would be significant). Interactions were removed from the model if they were non-significant, and the resulting model was a better fit for the data, as indicated by lower QICC values. The final model considered all the main effects as well as the interaction between age and the total time children spent exploring. Exhibit type (static or interactive) was not a significant factor in this model, Wald $\chi^2(1) = 0.48$, $p = 0.49$; neither was order of reflection, Wald $\chi^2(1) = 2.49$, $p = 0.12$. Children's age was a non-significant trend, Wald $\chi^2(1) = 3.07$, $p = 0.06$. The only significant differences were in the caregiver-child interaction styles, with children in child-led dyads showing higher levels of intrinsic motivation in their reflections (48%) than children in caregiver-led dyads (33%), $B = 1.14$, SE = 0.52, 95% CI [0.12, 2.16], Wald $\chi^2(1) = 4.84$, $p = 0.03$, and in the effect of total time spent exploring, $B = -0.03$, SE = 0.01, 95% CI [−0.05, −0.004], Wald $\chi^2(1) = 5.16$, $p = 0.02$, and the interaction between time spent exploring and age, $B = 0.0001$, SE = 0.0001, 95% CI [0.000003, 0.001], Wald $\chi^2(1) = 4.94$, $p = 0.03$. To investigate this interaction further, we performed a median split by age. For the younger half of the sample (children under 98.10 months of age, or approximately 8 years), children who said that they were intrinsically motivated to go to an exhibit explored longer overall (459 seconds vs. 442 seconds), while the older half of the sample showed the reverse pattern (440 seconds vs. 447 seconds). Neither of these differences, however, were significant, both r_s-values <0.05, both p-values >0.64.

We next considered whether children generated factual information regarding the exhibits in their reflections, which they did on an average of 30% of their reflections. We used the same analytic strategy on these data, looking at age, exhibit type (static or interactive), caregiver-child interaction style, total time exploring, and order of reflection. The final model here found no significant effect of reflection order, Wald $\chi^2(1) = 0.66$, $p = 0.42$. Exhibit type was a significant predictor: Children generated factual information when they reflected on static exhibits 33% of the time, significantly more often than they did so when they reflected on interactive exhibits (24% of the time), $B = 6.67$, SE = 2.03, 95% CI [2.68, 10.65], Wald $\chi^2(1) = 10.74$, $p = 0.001$. There were also significant effects of age and total time spent exploring. The mean age of children who generated factual information in a reflection was 100.31 months, while the mean age of children who did not was 96.09 months, $B = -0.15$, SE = 0.06, 95% CI [−0.27, −0.03] Wald $\chi^2(1) = 5.74$, $p = 0.02$. The mean time spent exploring when children generated factual information was 473 seconds, compared with 438 seconds when they did not, $B = -0.04$, SE = 0.01, 95% CI [−0.06, −0.01] Wald $\chi^2(1) = 9.14$, $p = 0.003$. There were also three significant interactions, between the caregiver–child interaction style and whether the exhibit was static or interactive, Wald $\chi^2(2) = 7.38$, $p = 0.03$, between age and exhibit type, Wald $\chi^2(1) = 8.13$, $p = 0.004$, and between age and time spent exploring Wald $\chi^2(1) = 7.07$, $p = 0.008$.

To consider the interactions with age further, we first performed a median split on the data set by age and reran the GEE analysis, focusing only on the difference between the static and the interactive exhibits and the total time spent exploring. In the younger half of the sample, children showed a trend to be more likely to generate relevant factual information for static exhibits (29% of the time) than interactive exhibits (17% of the time), $B = 0.61$, SE = 0.36, 95% CI [−0.10, 1.33], Wald $\chi^2(1) = 2.85$, $p = 0.09$. Children in the older half of the sample were also numerically more likely to generate relevant factual information for static exhibits (37% of the time) than interactive exhibits (32% of the time), but this difference was not statistically significant, Wald $\chi^2(1) = 0.24$, $p = 0.63$. Similarly, when children in the younger half of the sample generated factual information in their reflections, they explored the exhibits overall for longer (512 seconds) compared with when they did not generate factual information in their reflections (431 seconds);

5 One child chose not to stay for the post-exploration interviews, so these analyses are conducted on the remaining 51 participants.

this was a significant difference, $B = -0.01$, SE = 0.002, 95% CI [−0.01, −0.002], Wald $\chi^2(1) = 7.10$, $p = 0.008$. In the older half of the sample, there was no significant difference in time spent exploring when children generated factual information in their reflection (447 seconds) and when they did not (448 seconds), Wald $\chi^2(1) = 0.01$, $p = 0.94$.

Finally, we looked at the relation between caregiver–child interaction style and when children generated factual information. The main finding of interest here was that caregiver-directed children who were in the older half of the sample generated factual information in 71% of their reflections, compared with 20% for caregiver-directed children in the younger half of the sample. Child-directed dyads (35% vs. 28%) and collaborative dyads (29% vs. 24%) did not show this difference. Of importance, however, is that the majority of caregiver-directed children were in the younger half of the sample, and thus the 71% value indicates the reflections of only two children.

To summarize the findings in this section, children who were able to direct their own exploration were more likely to report internally motivated reasons for their exploration of particular exhibits. This suggests that the children we tested might have been better able to reflect on their motivations for their exploration when caregivers were less involved in setting goals for the interaction. Further, as children got older, they were more likely to be able to talk about the content of the exhibits, particularly when the exhibits they visited were static, suggesting that older children in the sample were more likely to be learning from those exhibits.

Children's reports on their own learning

Our final question looked at whether children reported that they learned something during their exploration, and what factors motivated reporting that they learned. Overall, 80% of the children stated that they learned something during their exploration of the exhibits. We examined whether there were significant correlations between children stating that they learned something during their exploration and the time spent exploring the static and interactive exhibits, the number of juicy moments at each type of exhibit, their overall level of engagement, and their caregiver-child interaction style. We only found two significant effects. First, there was a significant correlation between children stating that they learned something from their exploration and the level of engagement they showed during their exploration, $r(49) = 0.32$, $p = 0.02$. Second, there was a significant correlation between children stating that they had learned something and the number of juicy moments they experienced during their exploration of the static exhibits, $r(50) = 0.30$, $p = 0.03$. No other correlation was significant.

To examine these variables' independent effects, we constructed a binary logistic regression. While the overall model was significant, $\chi^2(2) = 8.91$, $p = 0.01$, only children's engagement predicted variance in children stating that they learned something, and only at a marginally significant level, $B = 0.90$, SE = 0.52, Wald $\chi^2(1) = 3.02$, $p = 0.08$, Odds Ratio = 2.47. Thus, children's reports about their learning seemed most influenced by their engagement with their exploration, and not any specific facet of the exploration itself.

Discussion

In this study, we recorded children's naturalistic exploration of a dinosaur exhibit in a natural history museum from a first-person perspective. We also interviewed these children following their exploration to gain further insight into how they viewed their experiences in the museum and how they thought about learning in general, using the videos they had generated as visual reminders. With this rich set of data, we can illuminate children's experiences in informal learning environments and explicate the role of different influences on children's exploratory behavior and their views of their own learning. In this way, this project can help us to gain a better understanding of how the exploration processes that we observe in the lab can unfold in real-world informal learning settings like museums.

The current analyses specifically aimed to investigate aspects of caregiver-child interactions in the exhibition and how these interactions related to children's engagement and to their reflections on their experiences in the exhibition. We found that children were more engaged with the exhibits when they interacted collaboratively with their caregivers, as compared to when they or their caregivers were leading the interactions. This aligns with results of earlier studies on caregiver–child interactions in museum settings, in which collaborative interactions led to the most engagement (e.g., Medina and Sobel, 2020; Leonard et al., 2021; Sobel et al., 2021; Sobel and Stricker, 2022).

We also found that children were more engaged the more they visited more static exhibits, which presented fossils and bones with explanatory plaques, than when they visited more interactive exhibits, at which they could pretend to dig for fossils or run on a treadmill to make a dinosaur skeleton move. Although older children spent more time at the static exhibits and less time at the interactive ones, the relation between children's level of engagement and time spent at the static exhibits held when controlling for children's age. Children were also more likely to generate particularly rich observations or interactions, which we called juicy moments, at static exhibits than at interactive exhibits. Exploration at the static exhibits also led to children reporting on more factual information, beyond simple descriptions of their actions at the exhibit, in their post-exploration interviews – a clue that they may have learned more from these exhibits.

These results are perhaps surprising from the point of view of museum design, because interactive exhibits provide more opportunity for children to choose their own actions and potentially to learn more or engage more deeply (see Falk et al., 2002; Falk and Dierking, 2018). Indeed, children in this sample tended to spend more time at the interactive exhibits, both overall and proportionally, which provides at least one indication that such exhibits were interesting to them.

To explain this pattern, we believe that it is productive to put this result into context with the relation between child engagement and caregiver-child interaction style. We found that children were more engaged when they interacted collaboratively with their caregivers, and static exhibits provide more opportunities for this kind of engagement. Caregivers tended to remain more hands-off when children were digging for fossils or playing in a green-screen room that allowed them to pretend to interact with computer-generated dinosaurs. Potentially, these interactive exhibits did not allow for the kind of collaborative interactions that led to higher engagement. Further, older children in the sample spent more time at the static exhibits and less time at the interactive ones. One possible reason for this could be that older children might be seeking out more collaborative caregiver–child interactive opportunities, although future work should aim to explore this relation in more detail. Understanding more about what leads to deep and genuine engagement at museum exhibits can benefit both museum design and our understanding of how children may learn in these naturalistic settings.

Finally, with respect to children's views of their own learning, children were more likely to say that they learned something during their museum exploration when they were coded as being more engaged by their exploration. We again saw an advantage for the time children spent at the static exhibits for this relation. Older children in particular tended to generate more factual information in their post-exploration reflections (information above and beyond descriptive information about what they had done or seen) when reflecting on their experience at a static rather than an interactive exhibit.

Although all of these findings require further investigation, they have the potential to translate into recommendations for museum practices. One of the primary recommendations from the current study would be to encourage more collaboration between children and caregivers in museum settings, perhaps through signage or guidance from staff. A second recommendation would be to think carefully about an exhibition's balance between static and interactive exhibits (see Dancstep et al., 2015): Children (especially younger children) enjoy interactive elements, but static exhibits seem to have an important role to play in children's engagement. Both greater engagement and longer dwell times at static exhibits related to children's generation of juicy moments; insofar as museums are aiming to encourage such moments, exhibit design could take these relations into account. Finally, the older children in the dataset were potentially more able to draw out educational messages from interactive exhibits than younger children, suggesting that exhibit design and messaging should be sensitive to the ways in which interactive exhibits may be interpreted differently by visitors of different ages.

Limitations and future directions

One of the main strengths of this project is in the rich, qualitative data that we have collected, particularly the first-person videos recorded by the children in this study. Because these data were collected within a naturalistic setting, with no direction from researchers about how to engage with the exhibition, they offer a unique view into children's genuine interactions in a museum environment. However, this choice of method also has several weaknesses, most notably in its lack of control. Children were allowed to explore the space in any way that they wished, meaning that not all of our participants saw all exhibits, and our participants explored these exhibits in different orders. Additionally, we put no restrictions on the kinds of interactions that children could have, meaning that some interacted with museum staff while others did not. Our dataset also includes several different types of family groupings, including multiple adults with a single child, multiple children with a single adult, and many others. While this tradeoff between naturalism and control allows us to be confident that our findings reflect a wide range of responses to our target exhibition, it does not allow us to go beyond the correlational results reported here. Future work should build on the current findings to investigate more fully how children and adults interact at static versus interactive exhibits, for example, which would allow us to strengthen the current conclusions about the value of static exhibits for enhancing children's engagement.

Another important limitation is that we only investigated children between the ages of 6 and 10 years old. Expanding our age range could allow us to add nuance to the current findings, since interactivity in exhibits is often geared toward younger children as a way of encouraging their engagement with museum content (particularly STEM content). Further, the older children in our sample might come to the museum with different exploratory goals than younger children. Along these lines, in this study, we were not able to consider what goals children had for their exploration of the exhibition prior to letting them explore. We did collect relevant information from the children's caregivers in our demographic questionnaire, but these did not relate to children's exploration or the caregiver-child interaction style (see the Supplementary materials section for details). Future research, however, could potentially interview children prior to their exploration as to what goals they have for their visit to the museum, and then see how their exploration is shaped by those goals. Future research could also focus more directly on the content of the exhibit, measuring children's knowledge about or interest in dinosaurs before and after their visit to the exhibit. This could help to clarify the extent to which the pedagogical goals of the exhibit are being met and what kinds of exploratory behaviors are most strongly associated with that kind of direct content learning.

Finally, our approach to analyzing these data has been to transform it into quantitative codes that align with previous literature in this area (e.g., Callanan et al., 2020), but we fully acknowledge that this does not capture the depth of what is happening in these videos. By making them public to the extent that we can (see footnote 3), we hope that other researchers will be able to apply their own analysis strategy to children's exploration in these videos and to use them as a resource to explore a wide range of other questions. This can enable the field to understand in more detail how children engage with and learn within informal learning environments.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://osf.io/8xghm/.

Ethics statement

The studies involving human participants were reviewed and approved by Institutional Review Board of Villanova University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin. Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

Author contributions

DW and DS jointly conceptualized the idea for this study and secured funding. DW was responsible for data collection, overseeing data coding, and writing the first draft of the manuscript. LD implemented two of the main coding schemes for the data, supervised by DW. DS conducted the analyses and implemented two other coding schemes. All authors have read, edited, and approved the submitted version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1110612/full#supplementary-material

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What would happen if?: A comparison of fathers' and mothers' questions to children during a science activity

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Parents' questions are an effective strategy for fostering the development of young children's science understanding and discourse. However, this work has not yet distinguished whether the frequency of questions about scientific content differs between mothers and fathers, despite some evidence from other contexts (i.e., book reading) showing that fathers ask more questions than mothers. The current study compared fathers' and mothers' questions to their four- to six-year-old children (*N*=49) while interacting with scientific stimuli at a museum research exhibit. Results indicated that fathers asked significantly more questions than mothers, and fathers' questions were more strongly related to children's scientific discourse. Results are discussed in terms of the importance of adult questions for the development of children's scientific understanding as well as broadening research to include interlocutors other than mothers.

KEYWORDS

scientific discourse, museum, parent–child interaction, questions, parent gender

Introduction

Children acquire knowledge about their world through interactions with adults such as parents (Vygotsky, 1978; Bruner, 1983). This may be especially true in scientific domains where such knowledge is often abstract or unobservable (Harris et al., 2006; Corriveau and Harris, 2014). In particular, parental talk about science promotes children's own ability to talk and reason about scientific causal relations and mechanisms (Leinhardt and Crowley, 1998; Crowley et al., 2001a,b; Callanan et al., 2002; Jipson and Callanan, 2003; Canfield and Ganea, 2014). This study examines parent and child scientific discourse, and specifically whether differences exist between mothers' and fathers' use of questions about science. Below we highlight our rationale for focusing on questions within science conversations and potential differences between mothers and fathers before turning to our study design.

Parental questions, in particular wh-questions (e.g., *why did that happen?*), scaffold children's development (Boland et al., 2003; Haden, 2010; Cristofaro and Tamis-LeMonda, 2012; Rowe et al., 2017). Compared to close-ended questions which can be answered with yes/no responses (e.g., *is the light on?*), wh-questions invite the child to continue the discussion and oftentimes engage in reasoning. Most studies have examined parental questions during book-reading and toy play (e.g., 3-bags task; Love et al., 2005) in relation to children's language development. For example, parental wh-questions during contexts such as free play and reading are more likely to receive a child response than close-ended questions and are predictive of young children's vocabulary development (Pancsofar and Vernon-Feagans, 2006; Pancsofar et al., 2010; Leech et al., 2013; Rowe et al., 2017).

In addition to language outcomes, there is accumulating evidence that wh-questions foster children's conceptual and scientific knowledge. Ash (2004) documented the types of questions that move parent–child conversation toward a higher level of scientific understanding by qualitatively examining three families' interactions at a science museum. Her findings suggest that questions that invite child explanations, are framed in an open-ended way, or build on prior conversations are most effective in promoting children's scientific discourse. During science interactions, parent–child conversations containing wh-questions are longer and more sustained (Benjamin et al., 2010), relate to better child memory and recall of the scientific principles discussed while engaged in the exhibit (Hedrick et al., 2009; Benjamin et al., 2010; Haden et al., 2014), and increase child scientific discourse (Callanan et al., 2017; Eberbach and Crowley, 2017).

In the current manuscript, we add to this literature by exploring the relation between parents' wh-questions and preschool children's scientific discourse. We focus on children's scientific discourse because prior research has indicated that children's scientific explanations – specifically causal and mechanistic explanations – are related to children's inductive inferences (Walker et al., 2014), generalizations (Legare and Lombrozo, 2014), and learning (Kurkul et al., 2021). Thus, it is important to explore how parental question-asking can prompt such science talk in young learners.

Our data were collected in a science museum which has several advantages including increasing access to both mothers and fathers. Traditionally, the literature on parent–child conversations has focused on children's interactions with mothers, given their historical role as children's primary caregiver. However, current demographic data in the United States indicate fathers play a considerably larger role in their children's development than in previous generations (e.g., Cabrera et al., 2018). An examination of potential differences between mothers' and fathers' questions in science contexts is warranted because interactional differences have been found in non-science contexts. During book reading and toy play, fathers, on average, ask more wh-questions than mothers (Rondal, 1980; McLaughlin et al., 1983; O'Brien and Nagle, 1987; Leaper et al., 1998; Rowe et al., 2004, although see Tenenbaum and Leaper, 2003 and Pancsofar and Vernon-Feagans, 2006 for reverse patterns). We are not aware of direct comparisons of mothers versus fathers wh-questions in scientific contexts.

This study describes data on conversations in a museum between four- to six-year-old children and their father or mother. Unlike some museum research which focuses on large-group interactions (e.g., Diamond, 1986; Allen and Gutwill, 2009; Gutwill and Allen, 2010), or examines language at the level of the conversation (e.g., Crowley et al., 2001b; Pattison and Dierking, 2019), we coded and analyzed every verbal utterance within dyadic parent–child conversations. The first research question examined potential differences in the frequency of wh-questions between mothers and fathers. To our knowledge, no studies have examined differential rates of questioning between mothers and fathers in science contexts. We predicted that fathers would ask more wh-questions than mothers based on meta-analysis data showing that fathers ask more wh-questions than mothers in non-science contexts (Leaper et al., 1998). We also anticipated that interactional differences between mothers and fathers might not be limited to wh-questions, but to additional features of parental talk. Thus, we also examined possible differences in mothers' and fathers' use of close-ended questions and statements (i.e., non-questions).

The second research question examined the relation between parental questions and children's scientific discourse. We predicted that children's scientific discourse would be positively associated with parental wh-questions. Because underlying scientific mechanisms are often invisible, we argue that wh-questions may be a particularly effective strategy for fostering children's scientific discourse. We also predicted that the frequency of parental wh-questions would be more strongly related to child scientific discourse than frequency of close-ended questions. Follow-up analyses examined whether these predictions were supported within both mother–child and father–child conversations.

In preliminary analyses, we explored child age and gender as potential covariates. Parents ask more questions to younger versus older children (Callanan et al., 2017), and talk more with "novices" versus "experts" (e.g., Palmquist and Crowley, 2007). Research indicates that the content of scientific conversations may also vary by child gender, for instance, explaining concepts more often to boys than girls (Crowley et al., 2001b) or using more challenging scientific language with adolescent boys (Tenenbaum and Leaper, 2003; Tenenbaum and May, 2014). Unfortunately, this study did not have adequate power to examine statistical interactions between child and parent gender, though we acknowledge this would be a fruitful topic for future research (see Crowley et al., 2001b).

Materials and methods

Participants

The sample included 49 English-speaking parent–child dyads recruited at a science museum in a large Northeastern city in the United States. Children (21 girls, 28 boys) were approximately 5 years, 5 months (M_{age} = 5.43 years, range = 4.00–6.91 years). Twenty-two mother–child dyads and 27 father–child dyads participated. Fourteen father–daughter, 13 father–son, 14 mother–daughter and 8 mother–son dyads comprised the sample. Ethnicity information was not collected for individual participants due to museum guidelines, but demographic information from the museum indicates it serves primarily European American families (Soren, 2009). Parents reported earning slightly higher than a bachelor's degree (Mean years of education = 17 years; SD = 1.85; Range = 12–20). There were no differences between mother (M = 17.14; SD = 2.24) and father (M = 17.23; SD = 1.50) educational attainment, $t(45) = 0.16$, $p = 0.87$. Further, there was no difference between mothers and fathers in STEM-related (e.g., engineer) or non-STEM-related (e.g., letter carrier) occupations, $\chi^2(1, N = 43) = 1.36$, $p = 0.24$. This study was approved by both the institution and museum ethics review boards.

Procedure

The data for this study were drawn from a larger study exploring a science learning intervention between parent–child dyads (see Chandler-Campbell et al., 2020). Here, we compare baseline data to explore potential differences parent-children science talk. Researchers approached families visiting the museum who appeared to have children in the study age range. If dyads agreed to participate, they were brought to a reserved corner of the museum's exhibit floor.

Semi-structured parent–child interaction

Data analyzed in the current paper come from semi-structured parent–child interactions with a balance scale. The scale contained with two bins balancing on each side and approximately 75 differently colored toy bears which could be placed in either bin. Dyads were invited to play with the scale together as they would typically do at home. The researcher sat to the side of the table, let the dyad play, and did not interrupt until the parent or child reported they were finished. All interactions were dyadic, that is, between the target child and parent. The semi-structured interaction was videotaped for later transcription and coding. After the interaction, parents completed a paper-and-pencil survey in which they indicated their educational attainment and current occupation.

Transcription and coding of parent–child conversation

All parent and child speech from the videos was transcribed verbatim by research assistants trained to reliably use the CHAT conventions of the Child Language Data Exchange System (CHILDES; MacWhinney, 2000). Each transcript was then independently verified by a second trained research assistant. The unit of transcription was the utterance, defined as any sequence of words that is preceded or followed by a change in speaker, intonation, or a pause. This process yielded 3,685 intelligible utterances across the entire sample, 2,407 of which came from parents (65.3 percent).

Parental question and statement coding

Trained research assistants coded each parent utterance for whether it was a wh-question, close-ended question, or statement. Every parent question utterance that was related to the balance scale activity was coded. We excluded any questions that were categorized as off-topic ($n = 44$; e.g., *what should we do later today?*).

Wh-questions

Question utterances that were framed with *who*, *what*, *when*, *where*, *why*, or *how* were coded as wh-questions (e.g., *what would happen if we put more bears on the left side? How does that work?*), the definition of which was adapted from Leech et al. (2013) and Rowe et al. (2004).

Close-ended questions

All remaining on-topic questions (e.g., *does it work? are you going to put that on?*) were coded as close-ended questions.

Statements

The number of statements, that is, non-questions, produced by parents (e.g., *this bin is heavier than this bin.*) was computed. Statements were counted by subtracting the number of questions from the total number of utterances produced. Total utterances were counted using automated analyses within CLAN (MacWhinney, 2000). Therefore, the sum of parent wh-questions, close-ended questions and statements reflect the total number of intelligible parental utterances produced during the interaction.

Scientific content coding

Parent and child utterances were also coded for references to scientific content. Two categories of coding were used: scientific and procedural, though analyses in this paper focus only on scientific codes. Scientific codes were defined as those that referenced a scientific fact (e.g., *how many bears are in this box? this is heavier than that bin.*) or causal process (e.g., *why is this bin heavier than this one; if you keep adding to this side it will go lower*). We coded utterances that made reference to balance, weight, or gravity, which were the scientific mechanisms inherent to the balance scale activity. Procedural utterances were defined as those which did not reference a scientific fact or mechanism; most were references to actions or directives (e.g., *put this over here; what one should we put in next?*).

Coding reliability

A team of research assistants was trained to implement the coding schemes described above. Research assistants were trained by coding 15 percent of the transcripts, which were compared to a gold standard set of codes prepared by the first two authors of the study. Once research assistants reached an acceptable level of reliability (Kappa > 0.70), they proceeded to code independently. Discrepancies in coding decisions were resolved through discussion between research assistants, and when necessary, a third coder was consulted. Coders were blind to study hypotheses and parent gender: transcripts did not mark whether the parent was a mother or father. Question and statement coding reliability averaged 95% (Cohen's Kappa = 0.90). Scientific content coding reliability averaged 88% with a mean Cohen's Kappa value of 0.75.

Measures

Time on task

Unlike laboratory studies in which parent–child interactions typically take place during a fixed amount of time, we allowed dyads to engage with the balance scale for an open-ended amount of time. Therefore, we calculated *time on task*, or the number of minutes that dyads engaged with the scale after the experimenter introduced the task.

Parent question and statement utterances

The total numbers of *wh-questions*, *close-ended questions* and *statements* were calculated for each parent using the CLAN program. Rates (utterances per minute) were also calculated to control for differences in time on task.

Parental scientific utterances

The CLAN program calculated *parents' scientific talk* by tallying the number of utterances that received a scientific code. We also identified and tallied utterances that received both a scientific code and a wh-question code, yielding a measure of *parents' scientific wh-questions*. Scientific talk variables were also converted into rates (utterances per minute) to control for differences in time on task.

Children's scientific utterances

Children's scientific utterances were calculated as the total number of child utterances that received a *scientific* code. We chose to collapse children's scientific questions and statements together because the majority of child scientific utterances were statements ($M = 8.44$; SD = 7.85) rather than questions ($M = 0.43$; SD = 0.93).

TABLE 1 Descriptive statistics of parent language codes (N=49).

Variable	Raw frequencies of utterances						Rate of utterances per minute					
	Mean (SD)	Range	1	2	3	4	Mean (SD)	Range	1	2	3	4
1. Wh-	6.53 (5.10)	0.00–18.00	–				1.57 (1.12)	0.00–4.31	–			
2. Close-ended	12.59 (11.16)	0.00–52.00	0.63***	–			3.10 (2.06)	0.00–8.52	0.39**	–		
3. Total questions	19.12 (14.89)	1.00–63.00	0.81***	0.96***	–		4.67 (2.70)	0.38–10.33	0.71***	0.93***	–	
4. Total statements	27.06 (17.12)	3.00–76.00	0.46**	0.48**	0.43***	–	6.84 (3.47)	1.94–18.31	0.13	0.25	0.24	–

** $p<0.01$; *** $p<0.001$.

TABLE 2 Descriptive statistics of parent–child conversation variables for mother–child and father–child interactions.

	Raw frequencies of utterances				Rate of utterances (per minute)			
	Mother–child		Father–child		Mother–child		Father–child	
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
Parent wh-questions	4.23 (3.95)	0–11	8.41 (5.13)	0–18	1.16 (1.05)	0–4.31	1.90 (1.06)	0–4.04
Parent scientific wh-questions	2.14 (2.46)	0–7	4.70 (3.71)	0–12	0.60 (0.61)	0–1.96	1.05 (0.82)	0–2.96
Parent close-ended questions	10.50 (10.50)	0–52	14.30 (11.40)	0–43	3.04 (2.14)	0–8.52	3.15 (2.00)	0–7.02
Parent statements	21.20 (13.00)	3–46	32.00 (18.60)	6–76	6.36 (3.54)	1.94–14.40	7.23 (3.42)	3.02–18.30
Parent scientific utterances	13.00 (20.10)	0–118	15.60 (12.30)	0–51	4.21 (3.62)	0–14.10	4.77 (3.55)	0–17.60
Child scientific utterances	5.30 (5.35)	0–16	11.50 (8.74)	0–33	1.88 (1.56)	0–5.45	2.74 (2.38)	0–11.00

Analysis plan

First, preliminary analyses examined whether key language variables differed as a function of child age and gender. Next, descriptive statistics for each parent talk variable was reported along with their inter-correlations. Finally, Poisson regression was used to compare mothers' and fathers' use of questions and the relation between parental talk and children's scientific discourse.

Poisson regression was used because there was significant variation in time on task across dyads, with the average dyad spending approximately 4 min (M = 3 min 52 s; SD = 1 min 40 s), although the range extended from 1 min 14 s to 8 min 50 s. Father–child dyads (M = 4.33 min; SD = 1 min; 40 s) interacted with the activity significantly longer than mother–child dyads (M = 3.33 min; SD = 1 min; 35 s), $t(48) = 2.14$, $p = 0.03$. Because of this difference, data were modeled using Poisson regression with time on task as an offset, which allowed us to model the rate of utterances observed per minute rather than the number of utterances used per participant. This ensured that any effect of parent gender on question use was not due to differences how long the dyad engaged with the activity. Offsets are an appropriate choice when the time period during which particular behaviors occur is not consistent across the sample (Gelman and Hill, 2006). When deciding on the appropriate offset, we considered both the total number of utterances, which is typical of other semi-structured protocol such as the three-bag task, and time on task. We chose the latter because the interaction was open-ended in terms of time, and any differences in time would in turn influence the total number of utterances.

Checks of model fit revealed evidence of over-dispersion, a violation of the Poisson assumption that the variance is equal to the mean. We refit models with quasi-Poisson distributions to allow for over-dispersion when necessary (Hardin et al., 2007). Over-dispersion can lead to biased standard error estimates, and the quasi-Poisson distribution corrects for this violation by widening standard error estimates for all predictors. All analyses were run using the glm2 package (Marschner, 2011) in R.

Results

Preliminary analyses

Preliminary analyses examined associations between child age, child gender, and key parental language variables (wh-questions, close-ended questions, and statements). No significant correlations emerged and thus we did not consider child gender or age as covariates in subsequent analyses.

Descriptive patterns of parent–child conversation

Table 1 presents descriptive statistics for each parent talk variable and their inter-correlations. On average, parents in this sample asked 19 questions and produced 27 statements during the balance scale activity. Parents asked significantly fewer wh-questions than close-ended questions, $t(48) = 4.76$, $p < 0.001$. A similar pattern of parents' question-asking emerged when question variables were considered as rates per minute (right portion of Table 1, *Frequencies per Minute*). Table 2 displays descriptive statistics (raw frequencies and rates per minute) for all conversational variables for mothers and fathers separately.

Comparing mothers' and fathers' use of questions

Poisson regression models examined whether use of wh-questions, close-ended questions, or statements varied between mothers and fathers (Table 3). Model parameters reflect the rate of utterances (per minute), but all findings held using the raw frequency of utterances. The only feature of parent talk found to significantly differ between mothers

TABLE 3 Poisson regression analyses for rate of questions and statements by parent gender.

	Parent talk variable (rates per minute)		
	Wh- *B* [95% CI]	Close-ended *B* [95% CI]	Statements *B* [95% CI]
Intercept	0.23 [−0.09, 0.53]	1.14*** [0.82, 1.43]	1.84*** [1.60, 2.06]
Parent Gender	0.43* [0.06, 0.81]	0.05 [−0.34, 0.44]	0.15 [−0.13, 0.44]

$**p < 0.01$; $***p < 0.001$. Parent gender was dummy coded such that 0 = mother and 1 = father.

TABLE 4 Series of regression modeling predicting children's scientific discourse (*N*=47).

	Model 1 *B* [95% CI]	Model 2 *B* [95% CI]	Model 3 *B* [95% CI]
Intercept	0.47 [−18, 1.09]	−0.50 [−0.43, 1.37]	0.96* [0.14, 1.71]
Wh-q per min.	0.36** [0.15, 0.57]	0.33** [0.10, 0.56]	0.003 [−0.42, 0.37]
Close-q per min.	−0.09 [−0.20, 0.02]	−0.12 [−0.36, 0.07]	−0.10~ [−0.21, 0.01]
Statements per min.	−0.001 [−0.07, 0.06]	−0.01 [−0.08, 0.06]	−0.01 [−0.08, 0.05]
Parent (father)		0.04 [−0.84, 0.97]	−0.63 [−1.51, 0.26]
Parent X Close-q per min.		0.06 [−0.19, 0.32]	
Parent X Wh-q per min.			0.50* [0.05, 0.98]
Adjusted R^2 (%)	31.1	31.2	41.3

$\sim p < 0.10$; $*p < 0.05$; and $**p < 0.01$.

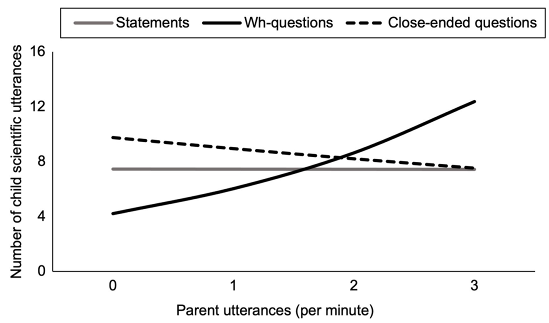

FIGURE 1
Parents' wh-questions are positively associated with children's scientific discourse (solid black line), whereas the effect of close-ended questions on child discourse is negative but non-significant (dashed black line). There was no association between parental statements and children's scientific discourse (grey line). Figure depicts estimates which were derived from Table 4, Model 1 using the Effects package in R.

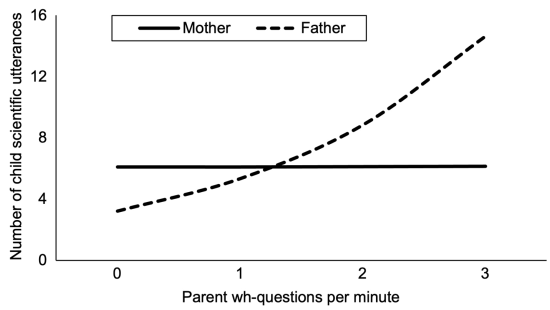

FIGURE 2
Estimated effect of parent wh-questions on children's scientific discourse. Figure indicates that this relation is moderated by parent gender such that fathers' questions are significantly and positively related to children's talk whereas mothers' questions are not. Estimates were derived from Table 4 Model 3 using the Effects package in R.

and fathers was wh-questions: fathers' rate of wh-questions ($M = 1.90$ questions per minute) was nearly twice the rate of mothers' ($M = 1.15$ questions per minute). The rate of close-ended questions did not vary by parent gender, nor did the rate of statements.

Relation between parental talk and children's scientific discourse

Next, we examined whether wh-questions, close-ended questions, or statements were associated with children's scientific discourse, and if so, whether parent gender moderated these relations. $N = 2$ children were not included in this analysis as their scientific talk was more than three standard deviations above the sample mean. Further inspection revealed that the inflated measures of scientific talk from these children were due to the majority of the time spent counting the elements to be placed on the balance scale. Table 4 presents a series of Poisson regression models predicting children's scientific discourse from main effects of wh-questions, close-ended questions, and statements, and their interaction terms with parent gender. Parental speech variables were entered in the same model for parsimony, as their correlations were non-significant or weak (Table 1). In Model 1 (Table 4), the positive coefficient for wh-questions per minute indicates that a higher rate of parent wh-questions was associated with more child scientific talk (Figure 1). Close-ended questions and statements were not significantly associated with child scientific talk.

Does parent gender moderate the effect of wh-questions on children's scientific discourse?

Table 4 (Model 2) shows that parent gender did not moderate the effect of close-ended questions on children's scientific talk (Table 4, Model 2). That is, the non-significant association between close-ended questions and children's scientific discourse was observed for both mother–child and father-child interactions. However, the significant interaction term in Table 4 (Model 3) reveals that parent gender moderated the effect of wh-questions on children's scientific talk. A follow-up simple slopes analyses suggested that fathers' questions positively related to children's scientific discourse ($t = 3.57$, $p = 0.001$), whereas mothers' questions did not, $t = 0.53$, $p = 0.60$ (Figure 2).

Why are fathers' but not mothers' wh-questions related to child scientific discourse?

Though not an *a priori* research question, we performed two exploratory analyses to better interpret the interaction between parents'

TABLE 5 Example scientific and procedural wh-questions from mothers and fathers.

	Scientific	Procedural
Mothers	1. Why do you think that is? 2. How many is that? 3. How do you think we can even that out?	1. What do you got in there? 2. What is it? 3. Now what should we do?
Fathers	1. Why is it like the balls? 2. How many would it take to level the that out? 3. If we keep putting them on this side what is that do?	1. What else can we do with this toy? 2. How do you want to do it this time? 3. Alright how can we do that?

wh-questions and gender. We analyzed (1) whether there was a difference in children's likelihood of providing an immediate response to father versus mother wh-questions, and (2) if fathers' wh-questions contained more scientific content than mothers' wh-questions.

First, to determine the role of child responses, we recoded every parental question (both wh-questions and close-ended questions) to reflect whether it received an immediate response from the child. Immediate responses were defined as a child verbal turn that followed directly from a parental utterance. Of the 937 parent questions, 348 questions received an immediate response from children (37 percent). Of those responses, 45 percent ($n = 155$ responses) were coded as scientific, 26 percent of children's total scientific utterances. To determine the likelihood of an immediate child scientific response, we fit a multilevel logistic regression model with adult question as the unit of analysis and participant as a random effect. In the model, we included question type (wh-, close-ended), parent gender, and their interaction term as predictors. Model results indicated a significant main effect for question type, $B = 1.43$; $z = 5.95$, $p < 0.001$. That is, the likelihood of a child scientific response was significantly higher for wh-questions than for close-ended questions, controlling for whether children were interacting with mothers or fathers. The main effect of parent gender was not significant, nor was the interaction term between question type and parent gender, $B = -0.39$; $z = -0.74$, $p = 0.46$. These latter effects suggest that in this sample, both mothers' and fathers' wh-questions were equally likely to elicit immediate scientific responses from children.

Second, we considered the possibility that fathers' wh-questions contained more scientific content than mothers', therefore prompting more scientific talk from children. To explore this possibility, we compared the number of scientific wh-questions across parent gender (see Table 5 for examples from the corpus). Parents, on average, asked 3.45 scientific wh-questions (SD = 3.49; Range = 0 to 12), comprising roughly 9.4 percent of their total utterances. Regression analysis confirmed that fathers asked significantly more wh-questions ($M = 1.05$ per minute; 11.0 percent of utterances) containing scientific content compared to mothers ($M = 0.60$ per minute; 6.8 percent of utterances), $B = 0.72$; $t = 2.02$, $p = 0.04$, [95% CI: 0.05, 1.46]. Thus, in addition to using more overall wh-questions, fathers also produced more scientific wh-questions.

The final step was to determine whether fathers' scientific wh-questions were more strongly associated with children's scientific discourse compared to mothers' scientific wh-questions. Regression analysis revealed a significant interaction between parent gender and scientific wh-questions, such that fathers' scientific wh-questions were more strongly associated with children's scientific discourse than mothers' questions, $B = 0.55$; $t = 3.14$, $p = 0.001$, [95% CI: 0.21, 0.89]. However, this model was over dispersed and once standard errors were corrected, the interaction effect only trended toward significance, $p = 0.11$. Thus, a conservative interpretation is that fathers' wh-questions—both scientific and procedural—are associated with more scientific discourse from children.

Discussion

This study examined children's science conversations with parents, specifically focusing on question-answer exchanges. A main finding of this study was that parental wh-questions were positively associated with child scientific discourse, whereas close-ended questions were not. Importantly, these findings were qualified by interactions with parent gender: fathers asked significantly more wh-questions than mothers, and the positive relation between parental wh-questions and children's scientific discourse was only found in interactions with fathers.

Our data indicated that children's scientific discourse was positively associated with the rate of parent wh-questions (per minute), and children were significantly more likely to respond scientifically to a wh-question, as compared to a close-ended question. Why might a higher rate of wh-questions relate to more child scientific talk? Controlled experimental studies offer some clues. Consider the difference between the following two parent utterances taken from our corpus of parent–child conversations. These utterances convey the same content but differ in whether the utterance functions as a question (A) or statement (B).

(A) How can we test the scale to see if it is unbalanced?
(B) Let us test the scale by putting the same number of weights on both sides.

Yu et al. (2018) propose that although both (A) and (B) transfer knowledge to the child, (B) would constrain a child's potential exploration and subsequent discussion about the scientific phenomenon. On the other hand, (A) expands the potential space of exploration and discussion about balance and weight between the parent and child. We argue that wh-questions during informal learning activities bring forward two situations that are known to scaffold children's science discourse: directing children's attention to important features of the activity (e.g., balance, weight), and prompting children to think and speak within their zone of proximal development (Vygotsky, 1978). Thus, it is plausible that although children may not always respond immediately to a question such as (A), the wh-question may lead to a subsequent scientific utterance later in the conversation. This framework is also useful in explaining may why close-ended questions were not related to children's scientific talk: close-ended questions likely constrain children's exploration and scientific talk to a similar degree as Yu et al. (2018) found with statements such as (B).

Although other studies point to the importance of parental wh-questions for children's learning (Benjamin et al., 2010; Haden et al., 2014; Callanan et al., 2017), this is the first study to directly compare children's responses to wh-questions versus close-ended questions as they occur around a scientific activity. Haden (2010) has argued that it is not the frequency with which parents ask questions, the more important aspect is *how* these questions promote learning. Our data supports this argument: in our sample, close-ended questions ($M=3.10$ questions per minute) were two times more frequent than wh-questions ($M=1.57$ questions per minute), yet close-ended questions were not related to children's scientific discourse. Differential relations between wh- and close-ended questions to children's talk holds important implications for educators and parents regarding how to facilitate children's engagement in informal, and perhaps formal, scientific contexts. For instance, an adult who asks only a few wh-questions may confer larger benefits for their child's engagement and learning compared to an adult who asks many close-ended questions.

The second major finding of this study was that fathers asked significantly more wh-questions than mothers. Results were presented in the rate of utterances (per minute) in order to control for differences in the length of time spent engaged in the activity. These results indicate that the density of fathers' wh-questions was greater than that of mothers', and this difference was not explained by the fact that fathers spent more time with children on the balance scale activity and therefore had more opportunities to ask questions.

This work is both similar to and different from prior work on mother and father conversation in non-scientific settings. For example, our work is consistent with Leaper et al.'s (1998) meta-analysis, indicating that one of the largest differences between mother and father interactions is use of wh-questions. Further, differences between mothers and fathers seems to be isolated: we only found that the rate of wh-questions differed, not close-ended questions or statements. This is similar to findings from Rowe et al. (2004) showing that only wh-questions differed between mothers and fathers, not total questions (which included close-ended questions). In contrast, however, other studies report that mothers ask more close-ended questions than fathers (Leaper et al., 1998; Tamis-LeMonda et al., 2012), which we did not observe in the current study.

These findings contribute to previous work showing that fathers' wh-questions during book reading and toy play at home are related to various indices of language and cognitive development between 24- and 36-months (Leech et al., 2013; Rowe et al., 2017). Our study broadens our understanding of fathers' challenging communicative style by showing these effects in other contexts such as the museum, with older children (i.e., 4- to 6-year-olds), and during interactions around scientific activities. Although parents in our sample were highly educated on average, previous work has found that fathers without a college degree also ask more wh-questions than mothers (Rowe et al., 2004). However, as questioning patterns vary by cultural context and reflect the broader socialization goals of that society (Schröder et al., 2013), it is important that generalizations of this study be limited to middle-class families in the United States.

Not only did fathers ask more wh-questions, but their wh-questions were more strongly associated with children's scientific discourse. A post-hoc analysis offered one explanation for this finding: fathers' wh-questions more often referenced scientific concepts, perhaps prompting children to engage in more scientific talk themselves. Of course, both speakers are co-constructing the conversation, and children are likely playing an important role in eliciting fathers' questions. To that end, an additional explanation we did not explore in this paper is the contribution of children's own interest and background knowledge of the topic. Children who demonstrate more interest in physical science may be initiating additional questions from parents, leading to extended back-and-forth conversation. Future research should explore the bi-directional associations between children's science interest and parents' language input. In addition, we did not explore the relation between scientific close-ended questions and children's scientific discourse, as theory and empirical data point to open-ended questions as more strongly related to scientific discourse. Future studies may consider how the delivery of scientific information using close-ended questions or statements relate to children's talk about science.

Fathers' high rate of scientific wh-questions adds to previous findings that fathers tend to challenge children to converse and reason beyond their current ability level (Gleason, 1975). However, when looking more closely at the likelihood of a child response, fathers' and mothers' wh-questions were equally likely to elicit children's scientific discourse. These results suggest that fathers' and mothers' questions are both an important element in supporting children's scientific discourse, but that the frequency with which fathers engage in this conversational move is more frequent than mothers. Indeed, Benjamin et al. (2010) found no difference in the rate of father and mother wh-questions after an experimental manipulation that instructed parents to increase elaborative talk such as wh-questions. This suggests that interventions which focus on boosting wh-questions may be equally beneficial to both mothers and fathers.

Though we did not observe that mothers' wh-questions related to child discourse, we must acknowledge other studies which have (e.g., Cristofaro and Tamis-LeMonda, 2012). One possibility beyond the scope of the present study is that mothers were using different conversational strategies than asking wh-questions while playing with the balance scale. For example, mothers have been found to engage in more supportive talk to children than fathers (Leaper et al., 1998). Thus, supportive talk may be positively influencing other aspects of the interaction, such as child interest or enjoyment, which were not measured outcomes in this study.

A limitation of this study is that the small sample size precluded us from potentially observing effects of both parent and child gender and their interactions. Although child gender was not significantly related to any parent or child conversational variables, it is possible that a larger sample size would have had the power to detect such effects. Furthermore, parent gender effects should be interpreted with caution due to the small sample size. Future work with larger samples should seek to replicate these findings as additional evidence of differences in maternal and paternal discourse patterns. A second limitation is that the current sample included a relatively small number of mother-son dyads. This was not by choice but reflected a recruitment decision to invite participation from any parent–child dyad visiting the museum who fell into the study age range. The unique and combined effects of parent and child gender are interesting and important and would be well-suited for a more controlled study outside of the museum where both parent and child gender are equally distributed.

An interesting direction for future research concerns whether the patterns of conversation around the balance scale—a physical science activity—would replicate in contexts that expose children to other scientific domains. There is evidence from the literature that conversational content varies based on the scientific domain of the activity: dyadic math and engineering talk is more common in science museum exhibits that focus on building, whereas biological science talk occurs frequently in settings such as aquaria and live animal exhibits (Rowe and Kisiel, 2012; Marcus et al., 2017; Kelly et al., 2022). Parent–child conversations in biological exhibits such as aquaria provide opportunities that the balance scale activity does not afford, such as talk about the life cycle and biological processes (Kelly et al., 2022). Touching and observing live animals in biological exhibits may also lead to opportunities for additional language interactions, such as comparing and contrasting and highlighting discrepancies (Rowe and Kisiel, 2012). However, there are likely conversational features that are common to all contexts, such as questions from parents, hypothesis testing, and a focus on general problem solving. Thus, future research should examine whether differences between mothers' and fathers' questioning patterns extend beyond the physical domain.

In summary, this study adds to existing evidence that parental wh-questions support children's participation in science conversations. We extend this work by showing that fathers, on average, asked more questions, which are associated with more scientific discourse from children. Fathers' strengths can serve as a unique and additive role to mothers in supporting children's developing conceptions about science.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Boston University IRB. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

KC and IC-C conceptualized the study design. IC-C, JA, and KL collected and coded the data. KL drafted the manuscript. KC, IC-C, and JA provided critical revisions. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Toddler home math environment: Triangulating multi-method assessments in a U.S. Sample

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Introduction: Current research has documented the home math environment (HME) of preschoolers and kindergarteners. Very few studies, however, have explored the number and spatial activities in which parents engage with children during their toddler years.

Methods: This study examined the HME of 157 toddlers using several methodologies, including surveys, time diaries, and observations of math talk. Further, it examined correlations within and across data sources to identify areas of convergence and triangulation, and correlated HME measures with measures of toddlers' number and spatial skills.

Results: Findings showed that, in general, uses of different types of math activities, including both number and spatial, were intercorrelated within method. Across methods, there was high intercorrelation between the frequency of math activities reported on parent surveys and the diversity of types of math activities endorsed in time diary interviews. Parent math talk gleaned from semi-structured interviews functioned as a separate aspect of the HME; different types of math talk shared few intercorrelations with engagement in math activities as reported in either surveys or time diaries. Finally, several HME measures positively correlated with toddlers' math skills.

Discussion: Given extant research demonstrating that both math activities and math talk predict children's math skills, our results stress the need for multimethod studies that differentiate among these HME opportunities.

KEYWORDS

math (STEM), toddler age, home learning environment, measurement, methodology, home math environment

Introduction

Early mathematics skills lay the foundation for later math achievement as well as academic skills more generally (Duncan et al., 2007; Jordan et al., 2007, 2009). Many of these math skills start to emerge during the toddler years when children begin to develop the symbolic number and spatial skills that we often think of in traditional conceptions of math. In terms of numeracy, by age two, children begin to understand the meaning of number words. Initially, children understand that number words form a category of words separate from other categories such as color words, and they may be able to recite the count list without fully understanding the meaning of these words. Around 2.5 years of age, most English-speaking children understand the word "one" and correctly give one object when asked for one in contrast to two or three objects. Over the next months and years, children incrementally develop an understanding for subsequent number words (Wynn, 1990, 1992). Likewise, toddlers show a rudimentary understanding of spatial perspective taking and mental rotation, such as understanding that turning a shape toy may help it fit in the designated hole, though these skills continue to undergo refinement throughout childhood (see Newcombe et al., 2013). Additionally, knowledge of spatial language is displayed in infants before their first birthday, but expressive spatial vocabulary is usually not demonstrated until the third year of life (Pruden et al., 2004).

Children's earliest environments can shape the development of their math skills, including their early interactions in the home with parents or other family members. A growing body of research addressing these opportunities for learning math, collectively referred to as the home math environment (HME), demonstrates that preschoolers' and kindergarteners' exposure to number and spatial concepts at home positively predicts math skills (Elliott and Bachman, 2018; Daucourt et al., 2021; Hornburg et al., 2021). Notably, however, few studies have examined toddlers' exposure to math concepts at home. Understanding children's HME in toddlerhood is particularly important given that, on average, toddlers spend more time in the home than do preschool- and school-aged children who spend a larger portion of their day in school settings. In this study, we examine different measures of the HME among toddlers, including surveys of math activities, time diary interviews, and observations of math talk, and assess how these measures relate. We compare measures of parent–child math activities, typically based on the frequency of specific activities or the diversity of different activities that children engaged in, and measures of how much parents talk about math during different semi-structured interactions with their children.

Measures of the home math environment

Although a long history of research has examined the home environments of infants and toddlers, much of this work addresses how parents provide opportunities for cognitive stimulation more broadly (e.g., Bradley and Caldwell, 1984; Foster et al., 2005; Chazan-Cohen et al., 2009; Rodriguez and Tamis-LeMonda, 2011) or engage in specific activities to support reading and language skills (e.g., Schmitt et al., 2011; Kim et al., 2015; Linberg et al., 2020). In contrast, less is known about the types of activities at home that might support toddlers' math learning. In this study, we use three methods of assessment of math activities with toddlers to help address this gap in the literature: traditional surveys, semi-structured observational tasks, and time diary interviews.

Parent surveys

Recent work with preschool- and kindergarten-aged children demonstrates that parents' reports of the frequency with which they engage in math-related activities at home with their children in surveys is positively related to children's math learning (see Daucourt et al., 2021, for meta-analysis). These positive links are primarily observed for activities that include number content, such as playing board games or counting objects (LeFevre et al., 2009, 2010; Siegler and Ramani, 2009). Math activities also include activities that have a spatial reasoning component, like playing with puzzles, building with blocks, or measuring objects, though these activities tend to be reported less frequently among parents of preschoolers than number activities (Zippert and Rittle-Johnson, 2020), and their links to children's early math skills are much less consistent than links between number activities and math (Hart et al., 2016; Purpura et al., 2020).

Time diaries

In contrast to traditional survey measures, time diaries offer a novel method of collecting data on families' day-to-day activities, where adults provide minute-by-minute reports of their activities over the course of a day (Phipps and Vernon, 2009). In past research using this approach, researchers have captured the amount of time children spend in various cognitively stimulating activities, such as reading or structured playtime (e.g., Hofferth and Sandberg, 2001; Fiorini and Keane, 2014). However, math activities may occur more sporadically throughout the day, and so additional probing for these interactions during interviews may be needed to obtain a more accurate view of number and spatial activities occurring at home. A recent study with parents of preschoolers found that very few parents spontaneously reported engaging in math activities during the day, but when asked whether specific activities occurred, almost all parents had engaged in some math activities with their children (Bachman et al., 2020). In other words, many math activities may occur in the context of other interactions, and parents tend to only report the larger activity within which the math activity took place. For example, parents may report baking with their children and not mention that they counted and compared measuring cups, but when asked about these specific behaviors, they report having engaged in these math activities. This additional probing may be particularly important for accurately measuring the frequency of math activities and will give rise to higher incidence of math activities than minute-by-minute reports of activities would suggest.

Although both survey measures and these probes embedded in time diaries rely on parental report of similar activities at home, time diaries may have some methodological advantages, including stronger ecological validity and fewer issues of recall bias. As an additional advantage, time diaries can assess duration of math activities, i.e., time in minutes spent engaged in activities, in a way that questionnaires do not because these typically focus on the number of days per week. On the other hand, by only asking about a select few days, the scale of the time diary reports is also much narrower than survey measures that often ask parents to report on larger periods of time, such as the prior week or two or even a whole month. Our past work with preschoolers suggests high levels of concordance between survey and time diary reports of math activities at home (Bachman et al., 2020), a finding we seek to extend here to a younger sample of children.

Parent math talk

As an alternative to parent reports of math activities, many researchers have measured math talk by examining how much and in what ways parents and children discuss number and spatial content, either during structured observational tasks that are math-related (e.g., Ramani et al., 2015; Leyva et al., 2017) or during naturalistic play or other everyday activities (e.g., Levine et al., 2010; Elliott et al., 2017). Much of the past math talk literature focuses on the frequency of children's exposure to number talk, or parents' use of number words, during the preschool and kindergarten years and how this number talk predicts children's number knowledge and math skills more generally (e.g., Mix and Cheng, 2012; Ramani et al., 2015; Elliott et al., 2017), with some nuances in the types of number talk and ways number talk is used (e.g., pairing the count list with cardinal values, or using larger number words). Similar patterns of associations are seen for children between one and 3 years of age, such that exposure to number talk in the toddler years predicts preschoolers' understanding of cardinality (Levine et al., 2010). Parents' use of number talk is likely context-dependent, as one study showed that number talk in a lab setting and observed at home were not significantly related (Thippana et al., 2020), Similarly, parents number talk tends to vary across different structured activities (Ramani et al., 2015; Zippert and Rittle-Johnson, 2020). Thus, in the present study we examine two contexts that may elicit number talk: a book reading task and a pretend grocery store activity.

Compared to number talk, less research has examined parents' discussions of spatial content with their young children, but the extant evidence demonstrates that the frequency of parents' use of spatial terms is positively related to children's spatial skills, possibly through children's own spatial vocabulary (Pruden et al., 2011; Polinsky et al., 2017; Casasola et al., 2020). Moreover, we recently showed that the complexity of parents' spatial talk as measured by the mean length of spatial talk utterances during a spatial activity predicted preschoolers' growth in spatial skills (Fox, n.d.). Much like number talk, parents' use of spatial talk varies depending on context and activity but in general is more frequent among activities that are inherently spatial, such as when building with blocks (Ferrara et al., 2011; Verdine et al., 2019; Zippert and Rittle-Johnson, 2020; Fox, n.d.). Although much of this work examines spatial talk frequency during the preschool years (age 4–5), more frequent parent spatial language use when children are between one and 3 years of age also predicts children's later spatial skills (Pruden et al., 2011). Here, we examine parents' use of spatial talk during a puzzle activity with their toddler.

Associations between the home math environment and children's math skills

Importantly, past work with children in early childhood demonstrates developmental differences and inconsistencies in the frequencies of home math activities as well as math talk and their relations to children's math skills, which could be due in part to the different methods used to measure HME (e.g., Hart et al., 2016; Thompson et al., 2017). For instance, Thompson et al. (2017) examined associations between HME, measured using survey methods, and math skills for 3- and 4-year-olds. In that study, correlations between HME and math were significant among the 4-year-olds but non-significant for 3-year-olds. However, a meta-analysis synthesizing results of more than 68 studies found that links between HME did not vary across age, though the youngest children sampled were 3-years-old (Daucourt et al., 2021). With respect to math talk, a study by Levine et al. (2010) showed that parental number talk at home to 2- to 3-year-old children predicted children's cardinality skills when they were four, while other studies do not find longitudinal associations between parents' frequency of math talk and children's math skills (Son and Hur, 2020; Fox, n.d.).

The discrepancies in previous studies exploring the link between HME and math skills in early childhood highlight the importance of additional research capitalizing on multiple methods to characterize the HME during toddlerhood. Indeed, the HME may be especially important in the development of math skills for toddlers, compared to preschoolers and older children, because once children enter preschool and elementary school, schooling effects contribute to math skills as well. Yet, few studies have examined the number and spatial activities in which parents engage with children during the toddler years. Thus, the present study provides rich description of toddlers' home math environments derived from multiple, interdisciplinary methods, including parent-reported questionnaires, semi-structured observational tasks, and time diaries. Additionally, this study will examine whether there is convergence within and across multiple modalities of HME measurement and provide exploratory correlations among HME measures and toddlers' early number and spatial skills.

The current study

Although talk about math concepts is likely to occur more frequently during activities that are explicitly math-related, conversations about number and spatial concepts can occur in everyday interactions and activities as well (Anderson et al., 2004; Susperreguy and Davis-Kean, 2016; Pruden and Levine, 2017; Thippana et al., 2020). As such, frequencies of math talk and math activities likely reflect distinct components of the overall HME (see Hornburg et al., 2021). Past work examining math talk and math activities in particular yields a mixed pattern of findings, with some studies demonstrating significant associations across measures (e.g., Thippana et al., 2020) where others find no correlations (e.g., Mutaf Yildiz et al., 2018). On the one hand, math activities are more likely to elicit math talk suggesting that more frequent math activities should also be associated with more math talk. However, in most of the published work, math talk is measured during non-math activities (e.g., free play, mealtimes), which may evince different amounts of math talk. Previous research has reported that parents' number talk during non-math activities is associated with parents' education and children's gender, while parents' number talk during math activities is unrelated to these factors (Thippana et al., 2020). Thus, it is possible that different factors influence when and how parents engage in math talk with their children in different activities resulting in different associations with frequencies of parent-reported math activities. In our own work with parents of preschoolers, we find little evidence of associations between the frequencies of parents' spatial and number talk and their reported spatial and number activities, either through survey measures or time diaries (Bachman et al., 2020). In this study, we aim to extend these analyses to a younger sample of children and consider how parents of toddlers engage in activities and have conversations related to math concepts with their children. Furthermore, we look at how these different measures of HME correlate with toddlers' early number and spatial skills.

Methods

Participants

This study draws data from the Parents Promoting Early Learning (PPEL) study, a longitudinal study of 157 parents and their toddlers (74 boys) studying parent factors and home experiences that bolster early math learning in toddlerhood. Children in this study were on average 2 years and 7.86 months old (SD = 2.47 months), ranging from 2 years and 4 months to 3 years 3 months of age. Participating parents were predominantly mothers ($n = 149$), but fathers ($n = 8$) also participated in this study. Most parents identified as non-Hispanic White (76%), with others identifying as Black (12%), Hispanic/Latino (3%), Asian (2%), or another race (3%). Parents also tended to be highly educated (76% had at least Bachelor's degree) and married (80%). Based on household income and family size, 22% of families were classified as low-income (i.e., earnings below 200% of the poverty line), 32% as middle-income (i.e., earning between 200 and 399% of the poverty line), and 46% as high-income (i.e., earnings 400% and above of the poverty line). Descriptive statistics are shown in Table 1.

Procedure

Due to the COVID-19 pandemic, this study was conducted entirely online through a combination of video conferencing calls, phone calls, and online surveys. Families were recruited from the greater Pittsburgh, Pennsylvania metropolitan area through online postings and advertisements on social media (e.g., Facebook), online research participant registries, and flyers distributed through local community organizations, preschools, and in parks. Study materials were delivered to families' homes, including assessment materials, toys, paper surveys, and, if needed, a laptop and Wi-Fi hotspot. Families participated in two Zoom calls with research assistants for approximately 30 min per session. During Zoom calls, children completed cognitive assessments, and the parent and child engaged in several play-based semi-structured interactions. The order of testing sessions was fixed, but the order of tasks within testing sessions was counterbalanced. All Zoom calls were recorded for later scoring of cognitive assessments and coding of parent–child interactions. Sessions were conducted, on average, about 1 week apart, though times between Zoom sessions ranged from as little as 1 day to as much as almost 3 months depending of families' schedules.

Parents also received two phone calls on separate days to complete time diaries reporting on the previous days. Calls were scheduled so that parents reported about activities on a work day and a non-work day. Finally, parents were sent an online survey including questions about demographic information and home learning activities. All research activities were approved by the local Institutional Review Board, and all parents gave written informed consent to participate in the study prior to completing any research activities. Families were compensated up to $100 for participating in the study. Data used in this study were collected from children and parents during the Zoom calls, phone calls, and electronic questionnaires. Measures of math activities were drawn from the online survey and time diary interviews. Measures of math talk were drawn from the semi-structured observations.

TABLE 1 Descriptive statistics of the sample demographics.

	M(SD)/%
Child age (in Years)	2 yrs. 7.86 mths (2.5 mths)
Child sex (Male)	47%
Parental family status (Married)	80.3%
Parents' race	
White non-Hispanic	76%
Black	12%
Asian	2%
Hispanic/Latino	3%
Other/multiracial	3%
Prefer not to answer	3%
Parents' education (Bachelor and higher)	76%
Parents' income	
Low income	22%
Middle income	32%
Upper income	46%

Measures

Home math activities

Parents completed questionnaires designed to assess the frequency of number and spatial activities at home over the last month (LeFevre et al., 2009). Parents were given a list of math activities in the home and asked to report how frequently they engaged with their children in each on a scale from 1 ("did not occur") to 5 ("almost daily"; LeFevre et al., 2009). These items were drawn from the work of LeFevre et al. (2009, 2010) and some were adapted to make them applicable to toddlers, include activities like "counting objects," "playing board games with die or a spinner," "learning simple addition," and "measuring ingredients when cooking." In our prior work, we identified three factors of numeracy activities, including those that address basic numeracy concepts (e.g., categorizing objects, identifying the meaning of number words), applications of number concepts (e.g., measuring ingredients while cooking, talking about money while shopping), and written numerals (e.g., reading number storybooks, playing with number toys; Elliott et al., 2023). Parents' responses were averaged to form these three number composites: number concepts (4 items, $\alpha = 0.69$); written numerals (4 items, $\alpha = 0.78$); and number applications (6 items, $\alpha = 0.66$). Similarly, responses on 5 items categorized as spatial activities were averaged into two separate composite scores tapping shape activities (3 items, $\alpha = 0.61$) and building activities (2 items, $\alpha = 0.63$). Higher scores indicate more frequent engagement with the number and spatial activities.

Math talk

Parents and children were observed while engaging in three semi-structured tasks designed to elicit either number or spatial talk. To elicit number talk, researchers provided dyads with developmentally appropriate toys for pretend grocery shopping, including a shopping basket, cash register, pretend money, and a play set of food items. Parents were instructed to play with these toys with their child as they normally would for 8 mins. Previous research has shown that a pretend grocery store can elicit high levels of math-related talk (Elliott et al., 2017). Parents and children also completed a shared book reading task. Dyads were given a wordless picture book created by the study team and designed to elicit number talk (Ginsburg et al., 2018). Parents were asked to read the book with their child and were prompted to finish the book reading after 3 mins. To elicit spatial talk, parents and children completed a magnet board puzzle task during which they were given magnets of various colors and shapes and asked to create an animal. Studies show that "guided play" tasks like this elicit high frequencies of spatial talk in parents and children (Ferrara et al., 2011). Dyads took up to 8 mins to complete the puzzle activity.

Each task was videotaped, transcribed verbatim at the utterance-level, and checked by trained research assistants. An utterance was defined as any language input from an individual speaker (either parent or child) that is bounded by silence of at least 2 s, a speaker transition, or a grammatical closure, e.g., a terminal punctuation mark such as a period (Pan et al., 2004). Transcriptions from direct observation tasks were coded for the quantity of parents' number and spatial talk. Specifically, the *total number of number utterances* during the grocery and book tasks was calculated, and then each number utterance was coded for the utterance content. We identified several types of number talk content that occurred during the grocery and book tasks, three of which were included in these analyses given their relatively high frequencies of use: (1) identifying *number symbols*; (2) *counting*; and (3) *labeling set sizes*. Number utterances involving comparing magnitude, ordinal relations, arithmetic, and patterns were coded but not used in this study because they were observed at such low frequencies (means ranging from 0.03 to 0.31 and medians of zero). The *total number of spatial utterances* during the puzzle activity was also calculated, and each spatial utterance was also coded for the utterance content. We examined three types of spatial talk that frequently observed during the puzzle activity: (1) discussing *shapes*; (2) *locations, directions, and orientations*; and (3) *deictics* (words whose meanings depend on the speaker's point of view, i.e., "here," "there," "where"). Two additional types of spatial talk were observed, but in such low rates that we were unable to include them in analyses. These were spatial dimensions and spatial properties, with the mean number of utterances of these types during the puzzle activity equaling 0.4 and a median of zero.

Coders for both number and spatial talk included graduate students, postdoctoral researchers, undergraduate research assistants, and full-time research staff. Following standard practices (Hallgren, 2012; Chorney et al., 2015), inter-rater reliability on the number and spatial codes for each task was assessed for over 20% of the sample by calculating the kappa statistics for each code between pairs of coders in identifying and categorizing each math talk utterance. Reliability was calculated at the utterance level from the full set of utterances. For example, when calculating reliability for utterances involving counting, cases of disagreement could include times where one coder did not identify the utterance as number talk at all and the second coded it as counting as well as times where one coder identified the utterance as a different type of number talk than counting when the second coded it as counting. This was the most conservative approach, since coders would have to both correctly identify an utterance as number talk and code it in the correct category of content or utterance type in order to count as agreement. The initial coder's classification was used in the case of disagreements. For number talk, coders examined a total of 2,014 utterances that were flagged as potentially number-related (based on their inclusion of number words or elicitations). There was a moderate to strong degree of reliability in labeling utterances across number talk categories ($\kappa = 0.83$–0.91; McHugh, 2012). For spatial talk, coders examined a total of 6,083 utterances. The coding of our spatial content codes also showed strong to almost perfect levels of agreement ($\kappa = 0.86$–0.93).

Time diary reports of diversity and duration of math activities

The diversity and duration of math activities was measured using the time diary interviews. Parents completed two time diary interviews over the phone collected using a modified format of the American Time Use Survey (ATUS; United States Bureau of Labor Statistics, 2016) during which they reported all activities carried out by parents and children over a work day and a non-work day. If the parent worked every day or was not employed, the time diaries were completed to reflect activities on a weekday and a weekend day. The phone interview occurred 1 day after the target day to facilitate accurate recollection of activities.

After parents reported the activities, they were surveyed at the end of the phone interview about the formal and informal home learning practices that occurred the prior day. These questions modeled survey items in LeFevre et al. (2009) work. These questions asked for occurrence of different activities, and if the activity occurred, the duration of the activity (i.e., parent reported time child spent engaged in an activity). Specifically, parents were asked whether a math activity occurred the previous day and were provided with a list of examples of this activity. If the parent said the larger category activity occurred, they were asked about the occurrence of a series of subcategory activities, giving a yes/no response, and to provide an approximate amount of time the child spent engaging in the activities. For example, parents were asked, "Did your child spend any time working or playing with numbers (both written and spoken)? This would include identifying names of written numbers (e.g., in magazines or in an elevator), identifying meaning of numbers (e.g., "how many is three"), or playing with toys that involve numbers (e.g., number fridge magnets, number stamping activities, foam numbers, etc.)?" If parents responded "yes" to working or playing with numbers, they were asked about occurrence and duration of all activities included in the broader category. The full list of items contained in the interview are listed in Table 2. From this list of items, we created measures of the *diversity of number activities*, which summed all number activities in which parents reported children engaged, and the *diversity of spatial activities*, which summed all spatial activities in which parents reported children engaged. We also summed across these measures to create a measure of the *total diversity of math activities*. Finally, we created a *duration of math activities* measure representing the total minutes in which children were engaged in all math activities.

Children's math skills

Children's *counting ability* was assessed using a task that asked children to count out loud on their own. If a child did not start counting independently after being asked by the researcher, the researcher would count up to two to help (i.e., "One, two, …. what comes next?"). Children were allowed to correct themselves or start

TABLE 2 Academic stimulation phone interview items.

	No	Yes	How long it lasted
MATH			
Did your child spend any time working or playing with numbers (both written and spoken)? This would include…			
Identifying names of written numbers (in magazines, in the elevator)			
Identifying meaning of numbers ("How many is three?")			
Playing with toys that involve numbers (e.g., number fridge magnets, number stamping activities, foam numbers, etc.)			
Did your child spend time counting?			
Counting objects (e.g., counting child's fingers, counting number or jumps or steps while playing, counting beads)			
Reciting numbers (e.g., 1,2, 3, 4,…)			
Counting down (10, 9, 8, 7, …)			
Did your child categorize or compare objects? So things like…			
Categorizing or organizing things by a common feature such as size, color, or shape (e.g., sorting blocks by color)			
Making collections (e.g., rocks, toy animals)			
Comparing things (e.g., by size, weight)			
Did your child talk with others about shapes or play with shapes?			
Playing with a shape sorter			
Talk about shapes or identify shapes? (e.g., What shape is this? Where do you see a square?)			
What about using math while shopping or cooking? So things like…			
Talking about money when shopping or while playing grocery shopping (e.g., "which costs more?")			
Measure ingredients while cooking or while pretending to cook (e.g., "We need two eggs and one stick of butter," "Can I have one more chocolate?")			
Compare food while eating (e.g., "who has the bigger plate, you or Mommy?" "Which of your strawberries is bigger?")			
Did someone talk to your child about dates or times? So maybe….			
Have conversations about time concepts (morning, afternoon, night, today, tomorrow, yesterday, "two days until your grandma comes")			
Timing (e.g., timing how long it took the child to complete a task, timing how many minutes)			
What about books or activities that involve math? This could include…			
Using rhymes that involve numbers ("1, 2, buckle my shoe" "Six little ducks went out one day…")			
Reading number storybooks			
Reading books to teach shapes			
Reading books to teach numbers (Counting picture books)			
Did your child play games that could involve math? This would include…			
Playing board games or cards that involve shape matching or counting			
Playing with puzzles			
Building Lego, blocks or construction set (Duplo, Megablocks etc.)			
Did your child use any video, computer games, or electronic toy focused on numbers or math concepts yesterday? Did you…			
Use educational software			
Play other videogames			
READING			
Did your child spend time reading with someone yesterday? This would include…			
Reading a story together.			
Reading signs or other non-book items with words on them.			
Child looked at books independently.			

(Continued)

TABLE 2 (Continued)

	No	Yes	How long it lasted
Did your child engage in story telling with someone? This can include...			
Outside of book reading, telling a story to your child			
Your child telling you a story that involved a sequence of events (e.g., beginning, middle, and end)?			
Did your child play sound or word games? This includes			
Play games with beginning sounds of words (e.g., cat starts with "cuh," Which word starts with /s/ like "snake"?)			
Play rhyming games with your child?			
Recite nursery rhymes that do not involve numbers?			
Sing songs with your child?			
Did your child engage in activities that involve letters? This includes			
Practice naming the letters of the alphabet.			
Ask your child to identify letters.			
Play with alphabet toys at home.			
Identify the sound of letters of the alphabet (e.g., asking "what sound does the letter D make?)			
Point out letters or words (e.g., directing your child's attention to words on street signs)			
Did your child use any video, computer games, or electronic toys focused on letters, letter sounds, or reading? Did you…			
Use educational software			
Play other videogames			

over again if they indicated that they made an error. They were stopped once they made a mistake or reached 100. Children's scores on this task were recorded as the highest number to which they were correctly able to count.

Spatial reasoning was assessed using the Point-to-Spatial-Relations task (Casasola, 2005), which measures children's spatial relation language comprehension. For each of seven trials, toddlers were shown PowerPoint slides (*via* Zoom screen share) of a stuffed animal posed with a red plastic cup. Children were prompted to identify the picture that matched the spatial relation between the stuffed animal and cup described by the researcher. The following spatial language terms were included: "on top of," "under," "between," "in front of," "behind," "in," and "next to." A proportion score was created for each toddler by summing the total number of correct responses and then dividing by the total number of trials completed by the child.

Analysis plan

To address our research aims, we examined patterns of correlations within each data source (i.e., parent questionnaires, math talk, and time diaries) and then across three data sources to identify areas of convergence and triangulation. Finally, we correlated children's early counting and spatial reasoning skills with the HME measures. Prior to running correlations, we addressed missing data in our sample. Level of missingness varied depending on the data source, ranging from no missing data for time diaries observations to a high of 13.4% missing (21 missing observations) for parent questionnaire data. In addition, some of the time diary duration entries were highly skewed and appeared to be errors in reporting (e.g., a report of almost 1,000 min or more than 16 h of math activities over 2 days). To address this, we recoded as missing any time diary duration measure that was greater than three standard deviations above the sample mean. Missing data were imputed using the multivariate imputation by chained equations (MICE) package in R to create 40 imputed datasets (Van Buuren and Groothuis-Oudshoorn, 2011). Our final analytic sample totaled 157 observations across all correlations.

Results

Parent surveys of home math activities frequencies

Table 3 presents descriptive statistics on parent responses to the survey items assessing frequency of math activities. According to the survey, children engaged in all types of math activities examined fairly frequently, with the lowest endorsed category being activities involving *number applications* (mean of 2.4 on a scale of 1 to 5). The other four categories, *number concepts*, *written numerals*, *shape activities*, and *building activities*, were reported more frequently, with means ranging from 3.2–3.8. Table 4 presents the correlations between the frequencies of math activities reported on the parent questionnaire. Engagement in all types of math activities captured in the parent questionnaire were significantly correlated, with correlations ranging from 0.17 to 0.62. Looking specifically at correlations within subdomains, number activities were moderately to strongly correlated with one another, with the strongest correlation observed between *number concepts* and *written numerals*. The two spatial activities composites, *shape activities* and *building activities*, also correlated modestly with each other. Significant correlations existed across number and spatial domains of activities. Indeed, the strongest correlation between math activities was observed between activities in different domains; engagement in *written numerals* and *shape activities* were the most highly correlated of all math activities reported.

Observations of math talk during semi-structured interactions

Number talk

As can be seen in Table 3, during the grocery and book tasks, the most frequent number talk involved *labeling set sizes*. On average, parents labeled set sizes about 16 times. Relatively less math talk involved *counting* and identifying *number symbols*. The intercorrelations between number talk utterances across tasks were positive and significant. As is shown in Table 5, talk concerning *labeling set sizes* was moderately correlated with *number symbols* and *counting* talk. Also, the total amount of number utterances was correlated with each of the three number talk content areas, with moderate correlations between total number utterances and *number symbols* talk and *counting* and very high correlations between total number talk and *labeling sets*.

Spatial talk

As is shown in Table 3, the amount of spatial talk across content areas was highly similar, averaging about 10–13 utterances per type. Types of spatial utterances were positively and significantly correlated, except for *shapes* and *deictics* utterances (Table 5). Moderate correlations were observed between *locations, directions and orientation* with *shapes* and *deictics*. Total spatial utterances were correlated with the specific content area utterances, with correlations ranging from 0.56 to 0.83.

Intercorrelations among number and spatial talk

In addition to within-number and within-spatial domains associations, we also analyzed whether parents who used more number talk also used more spatial talk during the observational tasks (Table 5). In terms of overall number and spatial talk, there was a positive correlation between *total number utterances* and *total spatial utterances*. Looking at specific content areas across domains, this correlation was driven by the correlation between *labeling sets* and talk involving *locations, directions, and orientation*. Parents who labeled more set sizes in the grocery and/or book tasks also tended to talk more about locations, directions, and orientation in the puzzle activity. There was also a small but significant positive association between *number symbols* utterances and *deictics* utterances. No other cross-domain correlations were observed when looking at the specific number and spatial talk content areas.

TABLE 3 Descriptive statistics for parental math support measures based on unimputed data.

	n	M	SD	Min	Max
Home math activities scale					
Number concepts (q)	150	3.76	0.87	1	5
Written numerals (q)	150	3.38	0.99	1	5
Number applications (q)	152	2.41	0.83	1	5
Shape activities (q)	152	3.23	0.91	1	5
Building activities (q)	152	3.72	0.99	1	5
Number talk					
Total number utterances (o)	157	25.39	17.75	0	81
Number symbols (o)	157	3.18	5.11	0	35
Counting (o)	157	6.14	7.23	0	50
Labeling sets (o)	157	16.07	11.11	0	53
Spatial talk					
Total spatial utterances (o)	152	31.96	14.58	5	73
Shapes (o)	152	10.48	7.97	0	36
Locations, directions and orientations (o)	152	12.88	8.87	0	52
Deictics (o)	152	13.98	8.16	1	42
Time Diary (TD) codes diversity of total math activities (td)	157	13.94	8.53	0	44
Diversity of spatial activities (td)	157	3.43	2.30	0	11
Diversity of number activities (td)	157	10.97	5.83	0	26
Minutes of math activities (td)	151	129.76	106.02	0	580

(q), survey of home math activities, (o), math talk content from the semi-structured observations, (td), math activities reported by parents in the time diary interview.

Diversity and duration of math activities based on parent time diary interviews

As noted in the methods, we used three measures from the time diary interviews that captured the diversity of number and spatial activities and the duration of math activities in which children engaged across the 2 days captured by the time diary. Descriptive statistics on time diary variables are shown in Table 3. On average, parents reported that children engaged in about three different spatial activities and 11 different number activities across the 2 days. The mean time spent engaging in math activities over 2 days was 129.76 min, with a standard deviation of 106.02 min.

Table 6 shows the intercorrelations between the two count variables (number activities and spatial activities) and the duration of time spent engaging in math activities. Not surprisingly, children who engaged in more total math activities tended to do more of both types of activities. Looking at the correlation between the different types of activities, there was a moderately strong correlation between the diversity of children's number activities and spatial activities. Additionally, the duration of time children spent engaging in math activities was moderately correlated with the diversity of math activities in which children engaged, including both number and spatial activities.

Intercorrelations across different methods of assessing math support and toddlers' math skills

In our analysis we also examined interrelations across the multiple methods of assessing math support. We present intercorrelations between number and spatial activities separately (Tables 7, 8, respectively). In order to examine whether these measures are also related to toddlers' early math skill, we correlated these measures with children's counting and spatial reasoning skills (Tables 7, 8).

TABLE 4 Pair-wise correlations among number and spatial activities at home as reported on parent questionnaire.

	1	2	3	4
1. Freq. number concepts				
2. Freq. written numerals	0.53***			
3. Freq. number applications	0.38***	0.41***		
4. Freq. shape activities	0.47***	0.62***	0.33***	
5. Freq. building activities	0.34***	0.27***	0.17*	0.34***

*$p < 0.05$, **$p < 0.01$, ***$p < 0.005$.

Number activities

The frequency of all three of the number activities asked about in the questionnaire (*number concepts, written numerals*, and *number applications*) were significantly and positively associated with the diversity of number activities endorsed in the time diary interviews, as well as with the duration of time spent doing math activities as reported in time diaries (Table 7). On the other hand, the observational measures of number talk had few correlations with the other number activity measures. The only type of number talk that was related to other number measures was *labeling sets*; it was positively correlated with the frequency activities involving *number concepts* and the diversity of number activities as reported *via* time diaries.

Spatial activities

We conducted similar analyses of interrelations among multiple data sources of parental support for spatial skills (Table 8). As with number activities, parents' reports on spatial activities of the survey were correlated with time diary reports of spatial activities. In particular, the frequency of engagement in *shape activities* and *building activities* were positively and significantly related to the diversity of spatial activities reported in time diaries. Similar to number talk, spatial talk was largely unrelated to parents' reports of spatial activities drawn from both the questionnaire and the time diary interview. The lone exceptions were a marginal relation between talk about *locations, directions and orientation* and the frequency of *building activities* and a marginal association between talk about *shapes* and the diversity of spatial activities reported in the time diary interviews.

Correlations with toddlers' math skills

Lastly, we examined concurrent validity between the HME measures and children's counting and spatial reasoning skills. For number activities (Table 7), the frequency of number concept activities and written number activities measured *via* questionnaire positively related to toddlers' counting skills. From the observational tasks, total number utterances also were positively correlated with counting, and this seems to be driven primarily by talk involving *labeling sets*. Time diary measures were unrelated to counting skills. Number activities

TABLE 5 Pair-wise correlations among number and spatial talk taken from semi-structured observations.

	1	2	3	4	5	6	7
1. Talk number symbols							
2. Talk counting	0.20*						
3. Talk labeling sets	0.38***	0.35***					
4. Total number utterances	0.61***	0.68***	0.88***				
5. Talk shapes	0.01	0.06	0.09	0.08			
6. Talk locations, directions, orientations	0.13	0.11	0.30***	0.27***	0.34***		
7. Talk deictics	0.19*	0.10	0.16	0.19*	0.06	0.41***	
8. Total spatial utterances	0.19*	0.1	0.32***	0.32***	0.56***	0.83***	0.68***

*$p < 0.05$, **$p < 0.01$, ***$p < 0.005$.

TABLE 6 Pair-wise correlations among measures of number, spatial, and overall math activities from time diary interviews.

	1	2	3
1. Diversity spatial activity			
2. Diversity number activity	0.66***		
3. Diversity of total math activities	0.74***	0.85***	
4. Minutes of math activities	0.50***	0.55***	0.46***

*$p < 0.05$, **$p < 0.01$,***$p < 0.005$.

were largely unrelated to spatial skills, with the exception that the diversity of number activities and total minutes of all math activities reported in time diaries were positively associated with spatial reasoning skills.

Table 8 shows results of correlations between the spatial HME measures and counting and spatial relation skills. Spatial measures were mostly unrelated to early counting skills, with the exception of a negative correlation with utterances involving *deictics*. In contrast, spatial skills were related to spatial HME measures. From the survey, frequency of *building activities* was positively related to spatial skills. From the observational tasks, the number of utterances concerning *locations, directions, orientations* were positively correlated with spatial skills. Lastly, the duration of time spent engaging in math activities, as reported by parents in the time diaries, was also positively related to toddlers' spatial reasoning skills.

Discussion

This study examined the home math environment (HME) of 157 toddlers using three distinct methodologies: survey questionnaires, time diaries, and observations of math talk. Looking across all three methodologies, it is clear that the parents and toddlers in this sample were frequently engaging in math activities and math talk. Comparing the descriptive statistics observed here with those from a preschool sample with similar methods and measures (Bachman et al., 2020), we see very similar frequencies of HME among toddlers and preschool-aged children. For instance, both toddler parents and preschool parents in the Bachman et al. study reported a mean of 3.7 on the frequency of building activities in the survey. However, the families with toddlers generally displayed comparatively higher levels of HME engagement than the families with preschool-aged children in Bachman et al. (2020). Specifically, looking at survey items, preschool parents in the Bachman et al., study reported a mean of 2.5 on the 1–5 scale for frequency of all number activities aggregated, while the toddler parents here reported between 2.4 to 3.8 on the three number activity subscales included. Similarly, the diversity of number and spatial activities reported in the time diaries averaged about 6.5 and 1.5 activities, respectively, for preschoolers (Bachman et al., 2020). In this study, toddler parents reported nearly double the amount of activities across the 2 days: about 11 number activities and 3.4 spatial activities on average. This finding is not surprising since toddlers may spend more time in the home, as attendance in non-parental care grows dramatically from age 2 to ages 4–5 (from around 45 to 75%; U.S. Department of Education, National Center for Education Statistics, 2021). Moreover, given that the discrepancy is most apparent in time diary reports, this suggests that using time diaries to assess HME in toddlerhood may be especially useful.

The primary aim of the present study was to extend past work triangulating measures of the home math environment to two- and three-year-old children in order to understand the opportunities for developing number and spatial skills that toddlers experience at home. We find that measures that address the frequency and diversity of parent–child math activities, including traditional survey measures as well as novel time diary interview measures respectively, are moderately intercorrelated with one another, whereas measures of math talk drawn from direct observations of parent–child interactions seem to reflect a separate, independent component of the HME. Given at least some past work with toddlers and older children demonstrating that both math activities and math talk predict children's math skills (e.g., Levine et al., 2010; Pruden et al., 2011; Daucourt et al., 2021), we argue that these dimensions are worthy of further exploration among younger children and stress the need for multimethod studies differentiate children's opportunities to learn math. Indeed, our correlational analyses show that both components of HME, math activities and math talk, demonstrate unique patterns of association with different aspects of early math skills.

It is important to note that despite modest correlations between the survey measures of frequency of math activities and time diary measures reflecting diversity and duration of math activities, our results suggest that both methodologies have unique concurrent validity and may be important to incorporate in any comprehensive measure of the HME. This is particularly clear when looking at correlations between HME measures and children's math skills. For instance, although the frequency of number activities (drawn from survey items) did not relate to spatial skills, the diversity of number activities and duration of math activities (drawn from time diaries) showed positive associations with spatial skills. It could be that the more comprehensive time diary prompts, which include example activities and are asked by trained interviewers, aid parents in recalling math-related activities that parents do not immediately think of as math activities when going through the survey items. In addition, the duration of math activities, which is only able to be accurately assessed *via* time diaries, was related to math skills.

Differentiating math activities and math talk

Despite the fact that math activities and math talk both expose children to math content, we find little evidence that these aspects of the HME are associated. Specifically, parents' use of number talk was not related to their reports of frequencies of number activities on either the survey or time diary measure. Likewise, parents who used more spatial talk with their children during a puzzle activity were not significantly more likely to engage in spatial activities at home. As such, we argue that engaging in frequent math activities and talking frequently about math reflect two unique methods of providing toddlers with opportunities to learn math in the early home environment. Math talk, which our results show relates to both early

TABLE 7 Pair-wise correlations among number measures across all methodologies and toddlers' number and spatial skills.

	1	2	3	4	5	6	7	8	9	10	11
1. Freq. number concepts (q)											
2. Freq. written numerals (q)	0.53***										
3. Freq. number applications (q)	0.38***	0.41***									
4. Talk number symbols (o)	0.11	0.13	0.02								
5. Talk counting (o)	−0.01	−0.04	−0.11	0.20*							
6. Talk labeling sets (o)	0.20*	0.11	0.12	0.38***	0.34***						
7. Total number utterances (o)	0.16	0.09	0.04	0.61***	0.68***	0.88***					
8. Diversity number activity(td)	0.31***	0.34***	0.23**	−0.03	0.12	0.16*	0.14				
9. Diversity of total math activities (td)	0.24***	0.25***	0.12	0.00	0.12	0.16	0.15	0.85***			
10. Minutes of math activities (td)	0.31***	0.23***	0.29***	−0.00	−0.03	0.08	0.04	0.55***	0.46***		
11. Counting	0.22*	0.23*	0.14	0.07	0.09	0.28**	0.23**	0.19	0.13	0.15	
12. Spatial skills	0.17	0.10	0.06	0.02	−0.02	0.06	0.03	0.21*	0.17	0.35**	0.29**

(q), survey home number activities, (o), number talk content from the semi-structured observations, (td), number activities reported by parents in the time diary interview. $*p<0.05$, $**p<0.01$, $***p<0.005$.

number and spatial skills, cannot be readily assessed *via* survey items. Indeed, math talk can occur during activities and interactions unrelated to math, like reading picture books, playing dolls, or playing outside. In our study, math talk occurred while children and parents engaged in pretend play involving the grocery store—an activity that is not inherently math-related and would not appear on a survey of home math activities.

Most research examining the HME in early childhood relies on measures of either parent–child math activities or parents' math talk, and few studies have examined how these factors may or may not overlap. Among parents of older children, number talk was observed more frequently in number-related activities such as board games than in other activities such as play with dolls or action figures, but number talk still occurred in these non-numeric activities, especially for parents with higher levels of education (Thippana et al., 2020). Similarly, past work suggests that parents use more spatial talk during explicitly spatial activities (Ferrara et al., 2011; Verdine et al., 2019; Zippert and Rittle-Johnson, 2020). Based on these past findings, we would expect that parents who engage in more number activities would in turn use more number talk. However, our measures of number and spatial talk reflect how parents discuss this mathematical content when given the necessary time and materials to engage in these activities, which may not be true in everyday interactions in the home. Alternatively, our measure of math talk, which was based on the frequency of utterances that included number or spatial content, may not capture the most important aspects of these interactions. Other metrics of math talk, such as the complexity of these utterances, may yield more informative measures of children's exposure to math content (Fox, n.d.).

In addition to extending this work to explore how parent reports of math activities and direct observations of parents' math talk relate to toddlers' math skills, there is also an open question regarding why parents might engage in one method of supporting math or another. There may be similar underlying characteristics that encourage or discourage a parent to engage in math activities and to talk about math, such that parents who report higher levels of math anxiety may select math activities less frequently with their children (e.g., Elliott et al., 2020) and also may discuss math concepts less often when interacting with their children (Berkowitz et al., 2021). However, given the lack of associations observed here, it is possible that factors that predict increased math talk may differ from those that predict engaging in math activities at home, particularly if parent–child activities reflect a more dyadic process and are shaped by structural constraints on families (e.g., Lleras, 2008; Bornstein, 2009; Snell et al., 2015; Elliott, 2020; Thippana et al., 2020). As such, engaging in math activities and math talk may represent two distinct approaches to supporting children's math skills for families, and considering these different approaches may help inform interventions aimed at boosting the home math environment.

Correlations between math activities and math talk measures further underscore the importance of measuring both aspects of the home learning environment. Both frequency of number activities and number talk positively predicted toddlers' counting and spatial abilities. And while neither diversity nor duration of math activities reported in the time diaries was associated with counting, both of these time diary measures were positively associated with early spatial skills. Looking across the associations between early math skills and all of the HME measures assessed here, our results suggest that all measures and methods of data collection provide valuable information regarding the home math environment and math development in toddlerhood.

Alignment between number and spatial content

Across all three methods of data collection, aspects of the HME focused on number and spatial content could be differentiated, and yet we found that parents' reports of number and spatial activities were moderately correlated, as were observations of number and spatial talk. For parent-reported survey measures, all intercorrelations among the three number factors and the two spatial factors reached statistical significance, and several of the strongest correlations were across number and spatial factors (e.g., shape activities and written numerals). Similarly, the correlation between the counts of different number and spatial activities from time diaries were also highly

TABLE 8 Pair-wise correlations among spatial measures across all methodologies and toddlers' number and spatial skills.

	1	2	3	4	5	6	7	8	9	10
1. Freq. shape activities (q)										
2. Freq. building activities (q)	0.34***									
3. Talk shapes (o)	0.05	0.06								
4. Talk locations, directions, orientations (o)	0.07	0.18*	0.34***							
5. Talk deictics (o)	0.04	0.11	0.06	0.41***						
6. Total spatial utterances (o)	0.09	0.15	0.56***	0.83***	0.68***					
7. Diversity spatial activities (td)	0.24***	0.23**	0.17*	0.05	−0.06	0.09				
8. Diversity of total math activities (td)	0.18*	0.13	0.33***	0.06	−0.10	0.15	0.74***			
9. Minutes of math activities (td)	0.19*	0.16	0.14	0.07	−0.01	0.11	0.49***	0.46***		
10. Counting	0.05	0.04	0.02	0.15	−0.25**	0.01	0.02	0.13	0.15	
11. Spatial skills	−0.04	0.21*	0.14	0.18*	−0.15	0.12	0.11	0.17	0.35**	0.29**

(q), survey home number activities, (o), number talk content from the semi-structured observations, (td), number activities reported by parents in the time diary interview. *$p < 0.05$, **$p < 0.01$, ***$p < 0.005$.

correlated. These findings are in line with previous reports of significant intercorrelations between number and spatial activities (Cahoon et al., 2017; Zippert and Rittle-Johnson, 2020), although others have reported no such associations (Hart et al., 2016; Purpura et al., 2020).

Additionally, parents' uses of number and spatial talk were moderately correlated. Notably, the observations of number and spatial talk were drawn from distinct tasks, and so this association demonstrates that parents who use more spatial talk in a spatial task are also more likely to use more number talk in an unrelated task. In other words, this association may reflect a more general underlying tendency of parents to use number and spatial talk with their young children rather than a task-specific effect. Alternatively, it could be that some parents are just more talkative in general when interacting with their child. Stated differently, the parents that are using more number and spatial talk during the tasks may also be talking about non-math related content as well during the task. Future studies that examine multivariate predictors of parental math talk could control for total talk to inform this issue.

Importantly, our cross-domain associations between number and spatial talk seem inconsistent with previous findings by Lombardi et al. (2017). They found that mothers' use of labeling set sizes during two different activities (playing with blocks and playing with a cash register and dress-up clothes) was unrelated to their support of learning spatial concepts while playing with blocks. However, the effect size in their study ($r = 0.2$) was very similar to the effect size in the present study ($r = 0.19$) suggesting that the larger sample size in our study ($n = 157$ compared to $n = 140$ in Lombardi et al.) may explain these discrepancies.

On the other hand, when looking at associations between number and spatial HME and children's counting and spatial reasoning skills, cross-domain associations were infrequent (i.e., spatial HME predicting counting and number HME predicting spatial skills). Counting, which is an indicator of children's early numeracy skills, was positively related to the frequency of number concept and written numeral activities as reported in the questionnaire and number talk (both total number talk and labeling in particular). Only one spatial HME measure was correlated with counting, and this was a negative correlation between math talk involving deictics and counting abilities. Although unexpected, deictics tend to be the simplest spatial location terms (e.g., "here," "there"), and children with more advanced math skills likely understand more complex spatial location terms, like "below," "underneath," and "behind." Accordingly, their parents may use fewer deictic words than the parents of children with worse math abilities, which would explain the negative relation between deictics and counting. Similarly, toddlers' spatial skills were positively predicted by frequency of building activities and parent talk related to location, direction, or orientation, as well as duration of math activities reported in time diaries. As with counting, only one number HME measure related to spatial reasoning (diversity of number activities from time diary reports).

Limitations

There are some limitations to this study that we must acknowledge. First, only one parent was observed with the toddler and responded to questionnaire and time diaries. This may underestimate the diversity and duration of math activities or math talk in the home environment if non-participating parents (or other people in toddlers' lives) engage in math with the children. Second, the correlations between math activities and toddlers' math skills may be obscured by the inclusion of only one parent's math talk and report of math activities. Children that are experiencing rich home math environments, but mostly with the non-responding parent, may have strong math skills related to math activities that were not captured by our observational tasks or parent reports since they occur with the non-responding parent or other adult.

Also, participants in this study tended to be more sociodemographically advantaged than the U.S. population as a whole, with more than three-quarters of the parents in the sample being highly educated (having a bachelor's degree or higher), married, and non-Hispanic White. Thus, results of this study may not generalize to a wider or more diverse population. This is especially true given documented associations in the literature between home learning environment and family socioeconomic status (e.g., Dearing et al., 2012; DeFlorio and Beliakoff, 2015; Galindo and Sonnenschein, 2015; Dearing et al., 2022). Accordingly, future studies must replicate analyses capturing and correlating surveys, time diaries, and observational measures of the HME with a larger and more diverse sample.

Lastly, this study uses cross-sectional data; all measures were drawn from a single window of children's toddlerhood. Thus, we are unable to provide any information regarding whether observed associations between HME measures are stable or change over children's development. Additionally, although we observed links between several of the HME measures and toddlers' math skills, the cross-sectional nature of these data prevents us from making inferences regarding whether children's HME experiences improve math skills, or, vice versa, whether toddlers with better math skills are inclined to engage in more math activities. Alternatively, the observed associations may be attributable to another, unobserved characteristic of children or families (Elliott et al., 2017; Thippana et al., 2020; Daucourt et al., 2021). Future research should explore these questions.

Conclusion

In comparing three measures of the HME, we find that parental reports of frequency of children's number and spatial activities on traditional survey measures correlate with a novel time diary approach to measure the diversity and duration of math activities. These findings are consistent with our past work with parents of preschoolers (Bachman et al., 2020) and highlight the potential utility of time diary measures for assessing the home math environment with less bias due to parental recall demands. More work is needed to explore this approach, however, and to compare predictive validity of time diary and survey measures of HME for children's later math skills. Additionally, we find that parents' talk about math during structured observations with their toddlers reflects a distinct, unrelated aspect of the home math environment, suggesting the need for more work exploring whether and how math talk in these interactions relates to children's math learning. Future work is needed to assess differential, longitudinal prediction of children's math skills over time across these various metrics, as well as to explore the characteristics of parents and children that explain individual differences in these behaviors. Nonetheless, these findings demonstrate the need for multimethod approaches to measuring the HME in toddlerhood in order to obtain a better understanding of the multitude of opportunities for learning math that young children experience in their daily lives.

Data availability statement

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by Human Resource Protection Office, IRB, University of Pittsburgh. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

PM drafted sections of the introduction and discussion of the manuscript, oversaw the writing process, and edited the full document. LE drafted sections of the introduction and discussion of the manuscript, and assisted with data analysis. TP performed that data analysis, and wrote parts of the methods and results section. CP was a data collector, helped support the literature review for the manuscript, and compiled the bibliographic information. SD supervised the number talk coding team and wrote sections of the manuscript describing this measure. DF supervised the spatial talk coding team and wrote sections of the manuscript describing this measure. EV-D guided data analysis and interpretation of the study finding. EV-D, HB, and ML helped to conceptualize the manuscript and provided feedback and editing of the manuscript at different stages of development. LC coded all measures drawn from the time diaries. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Science in stories: Implications for Latine children's science learning through home-based language practices

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There is growing interest in stories as potentially powerful tools for science learning. In this mini-review article, we discuss theory and evidence indicating that, especially for young children, listening to and sharing stories with adult caregivers at home can make scientific ideas and inquiry practices meaningful and accessible. We review recent research offering evidence that stories presented in books can advance children's science learning. Nonetheless, most of this work focuses on middle-class European-American U. S. children and involves narrative story books. Given the national imperative to increase Latine[1] representation in STEM education and career pursuits in the U. S., we argue that it is vital that we broaden the definition of stories to include oral narrative storytelling and other conversational routines that Latine families engage in at home. Cultural communities with firmly rooted oral traditions, such as those from Latin American heritage, rely frequently on oral storytelling rather than book reading to convey world and community knowledge to young children. Therefore, we advocate for a strengths-based approach that considers Latine families' everyday practices around science and storytelling on their own terms instead of contrasting them with European-American middle-class practices. We offer support for the view that for young children in Latine communities, culturally relevant oral practices, including personal narrative storytelling, can engender significant opportunities for family science learning at home.

KEYWORDS
storytelling, informal science learning, parent–child conversations, book reading, home learning, strengths-based

1 We use Latine to refer to individuals whose cultural background originated in Spanish-speaking Latin America.
The authors prefer to adopt the Spanish language gender inclusive ending "e" commonly used in Spanish-speaking countries, instead of the English term Latinx.

1. Introduction

In this mini-review article, we focus on the ways stories can advance children's science learning opportunities at home. Stories are culturally determined ways of communicating lived or imagined experiences (Bruner, 1996). Whereas most research and educational practice regarding stories centers on fostering language and literacy skills, there is growing interest in and evidence for stories supporting informal and formal science education (e.g., Brophy et al., 2008; Avraamidou and Osborne, 2009; Dahlstrom, 2014; Wilson-Lopez and Gregory, 2015; Cunningham, 2018). As we discuss, theory and evidence indicates that especially for young children, sharing stories can be a powerful vehicle for informal science learning in families. Paralleling the language and literacy work, most of the research on stories for science learning centers on story book reading. From our perspective, focusing on stories in books is not sufficient to realize the potential of stories to offer accessible and equitable science learning opportunities for young children. We argue it is necessary to broaden the focus on stories to include oral storytelling and other conversational routines that families engage in at home. This is especially important when we consider that among cultural communities with firmly rooted oral traditions, including those from Latin American heritage, oral storytelling rather than book reading may be a more common everyday practice for conveying knowledge to young children (Billings, 2009; Sánchez, 2009; Reese, 2012; Melzi et al., 2019). Unfortunately, the overreliance on print communication in formal and informal learning contexts often excludes such culturally relevant oral-based practices that can support children's science learning. What is needed is an emphasis on *ciencia en relatos* - science in stories - that includes understanding and leveraging oral practices that are cultural resources for supporting Latine children's science learning at home.

The motivation for this review is three-fold. First is the national imperative to broaden participation in science, technology, engineering, and mathematics (STEM). The U.S. Census Bureau reports that the Latine population reached 64.1 million in 2020 and is estimated to increase to 111 million by 2060, or nearly 28% of all Americans (Vespa et al., 2020). As the U.S. Latine population is increasing at a rapid pace, so too is the percentage of Latine students attending and graduating from college (Hussar et al., 2020). However, whereas 56% of the bachelor's degrees in science fields go to White Non-Latine students, only 13.5% are awarded to Latine students (National Science Foundation, 2019). To broaden participation in STEM education of groups underrepresented in STEM, we need to identify and promote strategies that respond to and value the experiences and funds of knowledge that students bring from their homes and communities (González et al., 2013; Bricker and Bell, 2014; Hernández et al., 2016). In particular, we know little about the socio-cultural and familial experiences of Latine children that can contribute to their early science skills and learning.

Second, research has established that early informal learning experiences in homes, museums, and libraries can foster lasting interest and knowledge of STEM (e.g., National Research Council [NRC], 2009, 2012; Sobel and Jipson, 2016; National Academies of Sciences, Engineering, and Medicine [NAS], 2018). For instance, parents' support of children's engagement with science activities predicts children's developing attitudes and later participation in science (Alexander et al., 2012). Further, parents' elaborative talk about science topics is related to children's engagement during hands-on activities, their later learning and memory of science-related experiences, and their interest in science (Tenenbaum et al., 2005; Benjamin et al., 2010; Jant et al., 2014; Callanan et al., 2017). Science practices such as asking questions, observing, explaining, and making predictions are both strengths of young children's everyday curiosity (Callanan and Oakes, 1992) and building blocks for more advanced STEM thinking (NGSS Lead States, 2013). Essentially, STEM learning opportunities involving family interactions at home and in other informal educational settings can open doors to future STEM educational and career paths. Nonetheless, such benefits may not be realized without uncovering and building on the experiences and practices of culturally and linguistically diverse families.

Third, although there is growing attention to science learning in Latine populations, too often this work takes a deficit approach by comparing Latine children with white, middle-class children and focusing on "gaps" in knowledge or practices (e.g., fewer books, less book reading). Instead, we advocate for work that can contribute to the strengths-based literature (e.g., Gutiérrez and Rogoff, 2003; Bang et al., 2012; Solis and Callanan, 2016, 2018), considering Latine families' everyday practices around science and stories on their own terms. For Latine families in the U.S., sharing oral stories is pervasive in everyday routines, and firmly rooted in Latin American oral traditions (McDowell et al., 1993; Delgado-Gaitan, 1994; Sánchez, 2009). Moreover, consistent with sociocultural perspectives on development (e.g., Vygotsky, 1978; Rogoff, 1990), the social-linguistic milieu of shared reading, storytelling, and other conversational routines can provide a setting for children's learning. This perspective drives a focus on culturally relevant oral practices, including personal storytelling, and efforts to understand how these social interactions can engender authentic and meaningful opportunities for Latine families' science learning at home.

Given the applied significance of our topic, the review that follows illustrates the ways that stories in books *and* those told orally by families at home can provide rich opportunities for science learning, and underscores the implications for broadening STEM participation among Latine children.

2. Stories for science learning

Notwithstanding the research and educational practices centering on stories for promoting language and literacy skills (e.g., Reese, 1995; Sénéchal, 2015; Wasik et al., 2016; Flack et al., 2018), there is a growing need to identify whether and how stories can support other academic skills, especially science learning. As with the work on language and literacy, the current research on stories for science learning focuses mostly on books, and involves white, middle-class U.S. children. However, we must build on Bruner's (1991) idea that oral storytelling is a natural form of human understanding that perhaps is more engaging for children and adults than scientific prose. Doing so encourages serious consideration of everyday home-based language practices of Latine families for whom stories in books may not be a primary way of conveying knowledge. Importantly, stories in books *and* told orally can convey science information that might not be available through direct experience and can boost children's engagement with challenging science-related ideas (Kelemen et al., 2014; Browning and Hohenstein, 2015; Evans et al., 2016; Cho and

Plummer, 2018). Stories also can be especially potent for making scientific ideas and inquiry practices meaningful and accessible (Graesser et al., 1980; Avraamidou and Osborne, 2009; Frykman, 2009; Klassen, 2010). By helping children connect with and see the importance of science problems, and how general and abstract science concepts can be applied to situations that are relevant to them, stories can motivate interest in and learning of science (Cordova and Lepper, 1996; Willingham, 2009; Murmann and Avraamidou, 2016) Moreover, stories can provide a springboard for elaborative discussions of science topics, involving cognitively challenging utterances about science and ideas, and scaffolding engagement in practices of science by caregivers and children (Haden, 2010; Solis and Callanan, 2018; Plummer and Cho, 2020; Shirefley et al., 2020). Embedding science information in stories can make representations of science-related knowledge and experiences stronger, more concrete, and meaningful (Haden et al., 2016; Marcus et al., 2023, in review). In these and other myriad ways, shared book reading and oral storytelling offer powerful mechanisms for children's science learning at home.

2.1. Science in books

Most of the work on science learning through book reading has involved empirical studies in which researchers read story books to children to teach biological (e.g., Tare et al., 2010; Ganea et al., 2011, 2014; Waxman et al., 2014; Walker et al., 2015; Strouse and Ganea, 2021) and physical science information (Venkadasalam and Ganea, 2018; Ganea et al., 2021). For example, Kelemen et al. (2014) found gains in 5- to 8-year-olds' understanding of natural selection after reading a storybook that conveyed the concept in narrative form. This was reflected not only in more accurate answers to test questions, but also more logical and coherent explanations applied to novel species, as well as children's retention of their increased understanding over 3 months. Other work shows that despite concerns that fictional story books could interfere with children's learning of science content (Ganea et al., 2014; Walker et al., 2015), fantastical content in story books might not hinder, and may even improve young children's participation and engagement with science-related ideas (Hopkins and Lillard, 2021; Hopkins and Weisberg, 2021; Richert and Schlesinger, 2022). Some scholars have proposed that narrative story books may be a more engaging and productive way to communicate science topics and scientific processes to learners than typical scientific expository texts (Kurth et al., 2002; Avraamidou and Osborne, 2009; Glaser et al., 2009; Dahlstrom, 2014).

Caregivers report that they primarily share narrative story books at home (Price et al., 2009; Robertson and Reese, 2017), although children may not have strong preferences for one or the other book type (Kotaman and Tekin, 2017). Theory and research in early education emphasizes offering young children a "balanced diet" of narrative, expository and other types of texts to support learning (Teale, 2003; Pentimonti et al., 2010; Robertson and Reese, 2017). Nonetheless, the use of expository texts with young children to relay factual information is increasing in educational settings (Saracho, 2017; Bergman Deitcher et al., 2019). Moreover, research shows that caregivers use more cognitively demanding questions, emphasize new vocabulary, and their children talk more, during shared reading interactions involving expository as compared to narrative books (e.g., Pellegrini et al., 1990; Price et al., 2009; Zucker et al., 2010). Some researchers and educators suggest that expository texts may be especially supportive of lasting learning, enabling the transfer of science information conveyed in books to present and future learning opportunities (Ganea et al., 2008, 2011; Richert and Smith, 2011; Kotaman and Tekin, 2017).

Although direct comparisons of science learning from narrative and expository texts are rare, some studies favor one or the other genre, whereas other studies indicate comparable or complementary science learning from both types of books (Torr and Clugston, 1999; Gonzalez et al., 2010; Pollard-Durodola et al., 2015; Nevo and Vaknin-Nusbaum, 2018). To illustrate the mixed results, consider that in Browning and Hohenstein (2015), 5- to 7-year-olds who were introduced to evolution using a narrative text expressed deeper understanding than did those introduced to the same ideas through expository text. In contrast, Walker et al.'s (2015) preschool-aged participants were more likely to generalize causal biological information from picture books to real world situations when they had learned the information from a realistic compared to a fantasy story context. For the 4 to 5-year-olds in Venkadasalam and Ganea (2018), genre did not predict science learning, so long as the books were similarly engaging and provided accurate information. Likewise, Aydin et al. (2021) tested 3- to 5-year-old children's learning of factual information about animals based on hearing both a storybook that contained anthropomorphism and a book that was non-narrative and did not include fantastical elements. Preschoolers in this study learned new facts about animals from both types of books. However, when the information in the narrative and expository books conflicted, older preschoolers tended to report information from the expository text; younger preschoolers showed no prioritization of information learned from one or the other book type.

2.2. Science stories and hands-on learning

A primary way that young children engage in science learning is through direct experience interacting with objects and the natural world (e.g., Piaget, 1970; Marin and Bang, 2018), and this is reflected in many early science educational opportunities for children in and out of school. When stories are combined with hands-on activities, stories can provide mechanisms for learning beyond what children might gain from hands-on engagement alone. To illustrate, several early childhood curricula pair book reading and hands-on STEM activities. Some involved specially crafted STEM-focused story books that provide visual depictions of math or engineering ideas, present problems for children to explore, and feature models for math or engineering investigations (Casey et al., 2004; Cunningham, 2018; Svarovsky et al., 2018). Engineering is Elementary curriculum units (www.eie.org; Cunningham and Lachapelle, 2014) begin with story books set in countries around the world in which the elementary-school protagonists solve problems with the help of adult engineers. There is evidence that these programs are effective, and in some cases, girls and children from groups underrepresented in STEM show particularly high learning gains (Cunningham, 2018; Svarovsky et al., 2018).

There are also an increasing number of researchers and educators seeking to understand the ways that stories in books, oral narratives, or picture-based narrative formats can advance informal STEM learning opportunities for children at home, and in libraries and museums (Pattison et al., 2020). In several studies, combining book reading or oral narratives with hands-on STEM activities in informal settings supported children's increased interest and knowledge of STEM (e.g., Luke et al., 2010; Evans et al., 2016; Murmann and Avraamidou, 2016; Pattison et al., 2017, 2018; Tzou et al., 2019; Plummer and Cho, 2020; Letourneau et al., 2022). As another example, in Callanan et al. (2021), some families engaged with a hands-on story-based museum exhibit that conveyed a non-verbal narrative about the life and death of a mammoth. These families, in turn, talked more about science in related exhibits containing fossilized mammoth bones, than those who did not use the story-based exhibit. In other work, oral stories told by STEM experts fostered family STEM learning conversations during hands-on museum and library programs (Siegel, 2019; Zimmerman et al., 2018; Solis et al., 2023, in preparation). Notably, although these latter studies connecting stories and hands-on activities have primarily focused on white, middle-class families, they do support a move to transcend book reading to understand the ways that oral stories can provide science learning opportunities for children.

3. Science in stories: Implications for Latine children

As this brief review indicates, science books can be used to support children's science learning. But there is still much to learn about the ways caregivers and children engage in science talk while reading science-related narrative and expository texts. Extratextual talk that goes beyond the printed word is likely important for science learning, just as it has been linked to development of specific oral language and early literacy skills (Haden et al., 1996; Fletcher and Reese, 2005; Hindman et al., 2008; Mol et al., 2008; Zucker et al., 2013). However, it is also the case that the few available studies with Latine families suggest that there may be distinctive patterns of associations between parental language during book sharing and child language outcomes with these families (e.g., Caspe, 2009; Escobar et al., 2017; Schick et al., 2017; Melzi et al., 2019). In these studies, Latine parents generally use less extratextual talk and fewer questions while sharing books with their children.

We need to address the serious gaps in current knowledge about the ways that caregivers from culturally and linguistically diverse backgrounds, and particularly Latine communities, may engage with science as they read books with their children. Nevertheless, this step is not enough if we want to capitalize on Latine family practices as points of leverage to support children's understanding of and interest in science. By broadening our consideration of science in stories to capture oral storytelling and other conversational routines, it is possible to gain purchase on the ways stories are cultural resources for Latine children's science learning at home.

While we acknowledge the diversity of Latine families as a result of their immediate and broader ecologies (e.g., country of origin, immigration histories, rural vs. urban upbringing, languages spoken), we also believe that Latine families share a set of core values and lived experiences, among these the widespread preference for oral practices. Ethnographic work in U.S. Latine communities, for example, shows that adult family members frequently use oral stories to impart lessons about life, provide education related to moral and social issues, and transmit cultural beliefs, values, and attitudes to their children (Delgado-Gaitan, 1994; Delgado-Gaitán, 2004; Espinoza-Herald, 2007; Cortez, 2008; Sánchez et al., 2010; Solis, 2017). Family reminiscing (i.e., conversations about shared past events), traditional stories marked by *dichos* (i.e., popular sayings), as well as *consejos* (advice), *refranes* (proverbs), and *adivinanzas* (riddles) are forms of oral discourse that Latine families use to support children's learning (Melzi et al., 2019). Work in Latin American communities outside of the U.S. documents a similar preference in families of young children. For instance, in Melzi and Caspe (2005) Spanish-speaking urban Peruvian families reported inventing and telling oral stories to their preschoolers more frequently than did English-speaking urban U.S. European-American families, who preferred book sharing. These everyday oral practices are formative, with research showing that oral sharing of stories with preschoolers predicts children's school readiness, including oral language and early literacy skills (Reese, 1995; Melzi et al., 2022) and cognitive abilities (Fivush et al., 2006). Yet, all too often, oral practices of culturally and linguistically diverse families are overlooked.

A focus on STEM-related oral practices among Latine families is supported by a growing body of research. Consistent with other work involving families of diverse educational and economic backgrounds (Bang and Medin, 2010; Solis and Callanan, 2016, 2021; Calabrese Barton and Tan, 2020; Huitzilopochtli et al., 2021), Latine families often engage in conversations about nature, and especially animals, plants, weather, and astronomy (Pérez-Granados and Callanan, 1997; Kelemen et al., 2005; Callanan et al., 2019; Shirefley et al., 2020; Castañeda et al., 2022). *Adivinanzas* (riddles) are used to entertain children, but they can rely on nature and other science-related topics thereby fostering children's knowledge and engaging them in science practices (e.g., analysis, explanation, interpretation). For example, in the following *adivinanza* (from Arreguín-Anderson and Ruiz-Escalante, 2018) the idea that plants have basic needs is conveyed through a simple riddle:

Adivinanza	Riddle
Siempre mirando al sol Y no soy un caracol. Giro y giro sin fin Y no soy un bailarín.	I always turn to the sun But I am not a snail, I endlessly turn, But I am not a dancer.
Respuesta: El girasol	Answer: The sunflower

Similarly, *dichos* (sayings) are told in families' homes to transmit wisdom and moral education. Some of these *dichos* are inspired by nature and people's interactions with nature. Thus, they provide opportunities for adults to explain the nature analogies to children, and in doing so expand their knowledge about life and science (Arreguín-Anderson and Ruiz-Escalante, 2018).

Looking ahead, we must advance current understanding of stories as cultural resources for Latine families' science learning at home. Doing so will not be easy because it requires moving away from a focus on book reading as a primary source of stories, as well as developing clearer understandings of how stories connect with hands-on activities in children's lives. Those of us who study stories for science learning need not to repeat mistakes of research concerning shared book reading and early literacy skills that sought to change Latine caregivers' behaviors, in turn, failing to produce the desired outcomes (see Melzi et al., 2019, for review). Efforts to support children's science learning are more likely to be successful when they build upon families' practices rather than seeking to replace them (cf. Melzi et al., 2022). However, insights into science in stories might still be limited without a corresponding expansion - even a "desettling" (Bang et al., 2012) - of definitions of what counts as science (see Huitzilopochtli et al., 2021; Pattison et al., 2022, for similar arguments). If we take a strengths-based approach that values the ways that science is manifested in Latine families' stories, it should be possible to uncover the science in stories that are part of these children's everyday, home-based language practices. Doing so will enable us to leverage their unique experiences to support Latine children's science learning, and ultimately, broaden Latine children's participation in STEM.

Author contributions

All authors developed the structure and content of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Investigating problem-posing during math walks in informal learning spaces

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Informal mathematics learning has been far less studied than informal science learning – but youth can experience and learn about mathematics in their homes and communities. “Math walks” where students learn about how mathematics appears in the world around them, and have the opportunity to create their own math walk stops in their communities, can be a particularly powerful approach to informal mathematics learning. This study implemented an explanatory sequential mixed-method research design to investigate the impact of problem-posing activities in the math walks program on high school students' mathematical outcomes. The program was implemented during the pandemic and was modified to an online program where students met with instructors *via* online meetings. The researchers analyzed students' problem-posing work, surveyed students' interest in mathematics before and after the program, and compared the complexity of self-generated problems in pre- and post-assessments and different learning activities in the program. The results of the study suggest that students posed more complex problems in free problem-posing activities than in semi-structured problem-posing. Students also posed more complex problems in the post-survey than in the pre-survey. Students' mathematical dispositions did not significantly change from the pre-survey to post-survey, but the qualitative analysis showed that they began thinking more deeply, asking questions, and connecting school content to real-world scenarios. This study provides evidence that the math walks program is an effective approach to informal mathematics learning. The program was successful in helping students develop problem-posing skills and connect mathematical concepts to the world around them. Overall, “math walks” provide a powerful opportunity for informal mathematics learning.

KEYWORDS
problem-posing, mathematics education, online learning, informal learning, math walk

1. Introduction

Much of the research in informal math learning has examined how people use math in their everyday lives and careers (e.g., Nunes et al., 1993; Civil, 2007; Walkington et al., 2014). There is a lack of research on mathematics in designed informal learning environments (Pattison et al., 2017), although this is a growing area of interest (Mokros, 2007). Such environments include museum exhibitions, libraries, and online games. Research suggests that although visitors are often unaware that they are engaging with math when in informal settings, promising mathematical thinking and social interactions can emerge (Pattison et al., 2017). Learning in informal environments often involves developing positive attitudes, enculturation, and socialization.

This is contrasted with formal settings, where learners may see mathematics as disconnected from their lives and daily activities (Mitchell, 1993; McCoy, 2005) and wonder, "When am I ever going to use this?" (Chazan, 1999). As mathematics becomes more complex and abstract, teachers in formal settings struggle to facilitate learning experiences that address this question (Gainsburg, 2008; Walkington and Bernacki, 2014). Accordingly, research has documented the incredible difficulty that learners have to make connections between math and the real world (e.g., Saxe, 1988; Lave and Wenger, 1991; Masingila et al., 1996; Inoue, 2005). Because of this, mathematics educators face a challenging question: How can we engage learners and allow them to see that mathematics is a rich and dynamic subject they can use to describe and understand their world? Leveraging mathematical reasoning as it happens in *informal* spaces can be a way to help students make these connections, and thus is an area in need of more research.

In this study, our approach to math walks draws on the successful characteristics of informal math learning, as well as on place-based education, where local communities are sites and resources for learning, and active engagement in the community is facilitated (Sobel, 2004). Math walks are activities where learners visit a series of different locations, physically or virtually, and observe and ask questions about how math appears in their surroundings. Our approach to math walks leverages the pedagogical strategy of *problem-posing*, where learners ask and solve their own mathematical questions. In the math walks program, youth experience mathematics in their surroundings (e.g., homes, communities, and school settings) and create math walk stops based on their observations of their surroundings. The math walk stops youth created consist of the math problems students posed and the corresponding solutions.

One challenge of designing informal learning environments was that some individuals could feel uncomfortable knowing that mathematics was involved in the environment, and they were expected to connect the environment with mathematical topics (Gyllenhaal, 2006). By leveraging the problem-posing strategy, individuals can choose the topics to pose questions about and embed their prior knowledge, interest, and social and cultural background into the problems. As a result, the problem-posing strategy can alleviate individuals' anxiety about learning mathematics during math walks and help individuals develop more positive dispositions toward mathematics (Fetterly, 2010). Mathematical dispositions refer to the attitude to see mathematics as something logical, useful, and worthwhile (National Research Council., 2001). However, the *combination* of problem-posing and informal mathematics learning has received very little attention in the research literature.

Problem-posing has been described as referring "to both the generation of new problems and the re-formulation, of given problems. Thus, posing can occur before, during, or after the solution of a problem" (Silver, 1994; p. 19). This broad definition makes it difficult for educators to learn about what a problem-posing activity should look like, how to implement problem-posing activities, and how to scaffold their students during problem-posing. Even though a positive relationship between problem-posing and students' mathematics learning has been documented, a gap between research findings in problem-posing and actual implementation remains (Cai et al., 2015). In addition, very few studies have looked at problem-posing in *informal* learning environments, even though problem-posing is an ideal approach in contexts where students do not need to follow a prescribed curriculum or standards and are free to generate a wide range of mathematical ideas and connections.

To contribute to the extant literature on problem-posing and bridge this gap between problem-posing's implementation in creating informal learning environments, this study investigated youth's problem-posing performance and procedure in a math walk program called "walkSTEM." It analyzed how this experience shaped students' dispositions toward mathematics. This study also aimed to look into youth's interactions with their peers and instructors by observing and analyzing their discussions and conversations when posing and solving math walks problems collaboratively. walkSTEM is an initiative in a large metropolitan area where youth, classes, and families take walks and find mathematical concepts and principles in the architecture, designed objects, art, and nature around them. When youth are tasked with creating their own math walks, they design "stops" on a math walk around their homes, communities, or schools, often leading their audience on the walk and explaining how mathematics is integrated into the surroundings. Since this study occurred during the COVID-19 pandemic, the math walks program that was implemented during a weekend extracurricular program for high school students was modified to be fully online. Youth met virtually with the instructors and other program members to watch existing math walk videos from their local communities and design their own walks collaboratively. In terms of their self-generated walks, youth can create walks around not only math topics but also other STEM topics. Even though most of the walks and the self-generated questions were related to mathematical topics, some youth in this program created questions related to biology, environmental science, statistics, and so on. As the objective of this program was to encourage students to connect their school-learned topics to real-world scenarios, the authors did not limit the topics to youth's self-generated walks. Given that remote learning has become more prevalent, this study explored the possibility of online math walks. It investigated both the advantages and challenges of implementing problem-posing and math walks through virtual formats.

The purpose of this study was to (a) investigate the problem-posing program's effects on youth's mathematical dispositions; (b) compare youth's problem complexity in different problem-posing tasks; and (c) explore the kinds of interactions youth have when creating math walks.

2. Theoretical framework

2.1. Problem-posing

Problem-posing "is a feature of broad-based, inquiry-oriented approaches to education" (Silver, 1994, p.21). Problem-posing has been an increasingly important research area in mathematics education in recent decades both in the United States (English, 1997; Walkington, 2017; Walkington and Hayata, 2017) and in other countries including China (Li and Lü, 2004; Chen et al., 2007), Singapore (Cai, 2003), Indonesia (Suarsana et al., 2019), and

Turkey (Salman, 2012; Ozdemir and Sahal, 2018). Researchers also conducted cross-national studies on problem-posing to explore the mathematical achievement differences between students of different countries (Cai, 1998; Cai and Hwang, 2002; Cai and Jiang, 2017).

Extant studies suggested that integrating problem-posing in students' mathematical learning can positively impact students' problem-solving skills, problem-posing skills, conceptual understanding, and dispositions toward mathematics (Brown and Walter, 1990; Silver, 1994; Silver and Cai, 1996; English, 1997; Cai, 1998; Cai and Hwang, 2002; Singer et al., 2013; Kapur, 2015; Walkington, 2017). Wang et al. (2022) conducted a meta-analysis on mathematical problem-posing interventions from 21 studies and concluded that the estimated average effect size of problem-posing on students' mathematical learning outcomes was 0.64 *SD*. The mathematical learning outcomes analyzed included problem-solving skills, problem-posing skills, mathematical dispositions, and mathematical achievement.

2.2. Metacognitive skills and mathematical dispositions

Problem-posing activities can promote both students' metacognitive skills (Karnain et al., 2014) and their mathematical dispositions (Silver, 1994; Wang et al., 2021). Specifically, suppose students are given a mathematical problem, they are required to generate some similar problems. Students need first to analyze the problem holistically (Silver, 1994) and understand the dynamics of the given problem (Priest, 2009) before they start to generate their problems. After posing the problems, students also need to develop a more thorough understanding of the logical relations among the problem texts, the question sentences, and the solutions to the problems they posed (English, 1997; Cai, 1998; Priest, 2009). During these processes, students may constantly self-monitor and self-regulate, thereby improving their metacognitive skills. Baumanns and Rott (2022) investigated the individuals' problem-posing process and identified these problem-posing-specific metacognitive behaviors: planning, monitoring and control, and evaluating. Research has also discussed how students' engagement with problem-posing could stimulate students' interest in mathematics learning and reduce students' mathematics anxiety, which includes fear and avoidance of learning mathematics (Brown and Walter, 1990; Silver, 1994). Given the various formats of problem-posing tasks, Stoyanova (1999) categorized problem-posing into three types: free, semi-structured, and structured problem-posing. In structured problem-posing tasks, students re-formulated given problems or generated problems based on a specific solution. In semi-structured problem-posing tasks, students generated problems based on a given problem structure or solution structure. In free problem-posing tasks, there is no specification of which type of problem to pose or which area the problem should be based on.

In extant literature on problem-posing, researchers also analyze the complexity of student-generated problems to investigate the relationships among students' problem-posing performance, problem-solving performance, mathematical achievement, and the type of learning tasks students are engaged in. Silver and Cai (1996) analyzed the mathematical solvability, linguistic complexity, and mathematical complexity of students' posed problems. The linguistic complexity was coded with the number of assignment, relational, and conditional propositions presented in the student-generated problems. The mathematical complexity focused on the number of mathematical semantic structural relations (i.e., change, group, compare, restate, and vary) in the problems. One example the authors provided was Did Arturo drive a longer time than Jerome and Elliot drove altogether in a regular way? This problem included five semantic relations: compare, restate, group, restate, and vary. In this study, the authors assessed 509 middle school students' problem-solving and problem-posing skills. The problem-posing task was a word problem statement without a given question. Students were asked to pose three different questions that could be answered with the information in the provided statement. The results suggested that stronger problem-solvers also tended to pose more complex mathematical problems than their peers who were not as strong in problem-solving. English (1997, 1998) coded the complexity of children-generated problems by coding problem type and the whether the problems required multiple steps to solve. English (1998) also compared the complexity of children-generated problems in formal (i.e., standard symbolic addition and subtraction sentences) and informal contexts (i.e., a large photograph of children playing with brightly colored items) and suggested that children posed more diverse and complex problems in informal contexts than formal contexts.

2.3. Scaffolding strategies for problem-posing

Unlike other learning activities, most students do not have prior experience with problem-posing. Therefore, it is important to provide students with peer support and a learning environment within which they are motivated to raise various questions. Most student-centered active-learning strategies, such as inquiry-based learning, problem-based learning, and discovery learning, can help to create such learning environments (Albanese and Mitchell, 1993; Bicknell-Holmes and Hoffman, 2000; Hattie and Yates, 2009). In these student-centered learning environments, students can learn at their own pace, take on active roles to create and synthesize their own questions and knowledge, and make connections to real-world issues (Barron et al., 1998; Bicknell-Holmes and Hoffman, 2000). In addition, utilizing appropriate scaffolding strategies can enhance students' problem-posing experience. Peer interaction is one of the most prevalent scaffolding strategies for problem-posing (Gade and Blomqvist, 2015). Kontorovich et al. (2012) proposed a framework to analyze students' problem-posing process that includes five aspects: task organization, knowledge base, problem-posing heuristics and schemes, group dynamics and interactions, and individual considerations of aptness. Group dynamics and interactions refer to the processes of social nature that occur when a group work on a problem-posing task together is included in the framework. The authors demonstrated the usefulness of this framework by using it to explain the different reactions students had when engaged in problem-posing activities, despite the similar background these students shared. The authors suggested that this framework could be used to do a fine-grained analysis of student's problem-posing work and could account for hidden mechanisms involved in students' decision-making when creating their own problems.

We previously conducted a pilot study that investigated young children's participation in a walkSTEM afterschool program where they were asked to pose problems (Wang et al., 2021). The findings suggested that children were able to create meaningful and interesting problems based on their observations of the school buildings and playground. Children were engaged in group activities during the math walks program: they experienced math walks created by previous students and posed more problems about the contexts; they walked around their campus and asked questions in groups; they voted for the places they were most interested in to create math walk stops at; they solved their self-generated problems with group members, and they created a final video to showcase their math walk to their friends and parents. During this process, children participated in free problem-posing first to get to know the concept of creating their own problems, followed by doing semi-structured problem-posing that modeled good problem-posing products, and then back to doing free problem-posing and creating problems about their school and communities. This sequence seemed especially effective in scaffolding children's problem-posing work. A recent meta-analysis on problem-posing (Wang et al., 2022) also compared how the different types of problem-posing activities could affect students' mathematical learning outcomes and concluded that implementing a combination of free, semi-structured, and structured problem-posing was more effective than only implementing semi-structured or structured problem-posing activities. In addition, the pilot study findings also indicated that children became more positive about learning mathematics and became more independent learners after attending the program. However, whether a similar dynamic could be facilitated in an *online* context with older students was not clear. That study also involved just 10 students who were in a school setting working with their math teachers. Thus we set out to follow this investigation with a new study investigating problem-posing with math walks in an online extracurricular program for high school students.

3. Materials and methods

This study employed a mixed-method research design (Creswell and Clark, 2017) to investigate problem-posing activities' effects on mathematical dispositions and the problem-posing performance of youth. This section presents the research questions, the research methodology, and the activities included in the online math walks program.

3.1. Research questions

This study aimed to utilize the mixed-research design to comprehensively analyze youth's learning process and dispositions in this online math walks problem-posing program with qualitative and quantitative analyses. With the quantitative analysis, this study examined the trajectories of problem-posing performance throughout the program and compared dispositions toward mathematics before and after the program. With the qualitative analysis, the authors analyzed problem-posing work throughout the program and youth's interviews to further analyze how problem-posing shapes youth's mathematical interests and dispositions and what interactions occur among youth when they pose problems and create their own math walks. The research questions are as follows:

(1) *How does designing and leading a math walk shape youth dispositions toward math and toward creating their own math problems?*
(2) *How does the complexity of the mathematical problems students generate as part of their math walk activities vary over the course of the program?*
(3) *What interactions do youth have with their peers when they pose problems and design their math walk questions and stops?*

3.2. Methods

3.2.1. Participants

Participants were recruited from an existing extracurricular college preparation program in a university located in a large southwest metropolitan area. The program's objective is to help first-generation students from designated schools who desire to pursue college transition from high school to college. Activities were enacted during Saturday morning sessions. The program accepted students from 10 schools, where 76.45% of the students are economically disadvantaged, and 24.38% are English learners.

In total, 35 students were recruited (26 Hispanic, seven African American, one Asian, and one student who identified as two or more races). Among the 35 students, there were 24 female and 11 male students. All participants were high school students, and there was one freshman, 13 sophomores, four juniors, and 17 seniors. The 13 instructors (11 females and two males) in this program were tutors in the college preparation program, who were all undergraduate students from this university. Of the 13 instructors, seven were Hispanic, three were White, two were Asian, and one was African American.

3.2.2. Problem-posing activities in the online program

In the virtual math walks program, there were three main problem-posing activities for students: watching walkSTEM videos and posing their own problems based on those videos, taking #STEMlens photos and posing problems based on those photos, and creating virtual math walks and presenting the walk in small groups.

The walkSTEM videos were short videos in which prior youth or informal STEM educators discussed STEM-related problems in their surroundings. The STEM problems could be based on a place (e.g., a museum, a shopping mall, and a park), an activity (e.g., playing basketball and playing music), or a STEM topic or concept (e.g., geometry and biology). After watching the videos, students were asked to complete a video-watching questionnaire (see Appendix A). Students documented the questions being asked in the video, explained how the video was related to mathematics, and created problems about the scene or the object in the video. The #STEMlens photo was a problem-posing activity in which students took photos of their surroundings, marked up the photos using photo-editing tools, and posed problems based on the photo and markups. Students' #STEMlens photos were assessed by their instructors using the rubric presented in Appendix B2. Creating a STEM walk was the final project of the program. Each student designed three walk stops, and each stop was comprised of a #STEMlens photo or a short video, a STEM question about the photo/video that students posed, and a corresponding answer or a strategy to answer the question. Students worked in groups to provide feedback and suggestions to each other. Each selected one stop from their STEM walk and presented in groups to their peers, parents, staff, and instructors. The project and the presentation were scored by their instructors using the rubrics in Appendix B1. Among these three activities, the problem-posing work in the video-watching activity would be considered semi-structured problem-posing, according to Stoyanova (1999), as students were asked to create problems based on a given picture or scene. On the other hand, the problem-posing in #STEMlens and the Final Walk project would be categorized as free problem-posing. Students were allowed to pose problems based on objects in their own surroundings.

Students met with their instructors nine times for the program during the semester, including three longer sessions (one 90-min session and two 120-min sessions), five 30-min check-in sessions, and one final presentation session. The researchers, the program coordinators, and the college preparation program staff met with the instructors for training purposes before implementing the program. More descriptions of the instructional activities in each session are listed in Table 1, and the researcher provided detailed lesson plans for all sessions to instructors before each session.

TABLE 1 Student activities in each math walk session.

Session	Math walks program activities
Session #1	Students completed the pre-survey. Instructors introduced the walkSTEM program, the gameboard, and the #STEMlens photos. Students watched one walkSTEM video and completed the video-watching form
Session #2	Students watched three walkSTEM videos and completed three video-watching forms. Instructors checked in with students regarding their #STEMlens photos
Session #3	Instructors checked in with students regarding their #STEMlens photos. Students submitted at least one #STEMlens photo. Students who finished earlier would watch two more walkSTEM videos and complete the forms
Session #4	Instructors introduced the Final Walk project to students by watching previous student-created Final Walk videos. Each student completed a Final Walk project planning sheet and started to work on the first two math walk stop design worksheets
Session #5	Students completed the first two math walk stop design worksheets and finalized at least one math walk stop, including the question, the photo/video, and the response to the question for the stop. Students who finished early would watch one more walkSTEM video and complete the form
Session #6	Students started to work on the third math walk stop design worksheet, watched one walkSTEM video, and completed the form
Session #7	Students worked in groups to each select one math walk stop from their projects to form a group Final Walk. Students gave feedback to each other, wrote the script for their Final Walk, and created the slides for the presentation on STEM day
Session #8	Students finalized their group's Final Walk presentation and rehearsed
Session #9	Students presented their group's Final Walk to their parent's peers. Students completed the post-survey after the presentation

3.2.3. Measures

Research data were collected through six sources: the student pre- and post-survey, the instructor pre- and post-survey, the instructor mid- and post-interview, the student post-interview, the students' problem-posing work, and the video recordings of all of the meetings.

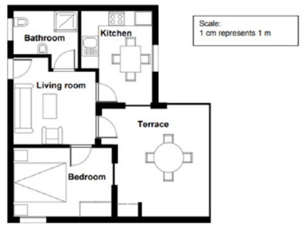
The students' pre- and post-surveys are presented in Appendix C. Students took the pre-survey during their first meeting, which included questions about demographic information, problem-posing, problem-solving, conceptual understanding, procedural fluency, and mathematical dispositions items. The student post-survey was implemented after the final presentation day, and the post-survey only included items on students' problem-posing skills and mathematical dispositions. The dispositions survey items were adapted from the mathematical individual interest scale from Linnenbrink-Garcia et al. (2010). Cronbach's alpha for the mathematical interest scale was 0.90, which indicates good reliability. The procedural fluency, conceptual understanding, and problem-solving items were selected from TIMSS 2011 grade 8 mathematics assessment (Mullis et al., 2012). The overall Cronbach's alpha for the TIMSS 2011 achievement scores was 0.97 (Bofah and Hannula, 2015).

Students who participated in all three problem-posing activities were selected to be interviewed using the interview protocol in Appendix D after their final presentations. The interview protocol focused on students' problem-posing experiences in the program, the difficulties or challenges in generating problems, and whether students' mathematics dispositions had changed after participating in this program.

3.2.4. Coding and analysis

Student-generated problems' content complexity and students' ratings in the mathematical dispositions survey were the main quantitative outcome variables in this study. The content complexity was coded with the criteria adapted from Liu et al. (2020). The coding categories with examples and problem-posing prompts for the example problems are presented in Table 2. We coded student-created problems on a scale of 0–5, where 0 is the least complex and 5 is the most complex. We measured the complexity of the problem from three perspectives: whether the

TABLE 2 Content complexity scoring examples.

Category	Score	Examples	Problem-posing prompts
Not-relevant or incomprehensible	0	All circles together. (Prompt A)	Prompt A  Prompt B  Pose a mathematical problem based on this apartment floor plan or this apartment
Relevant statement	1	This could be a probability question. (Prompt A)	
Relevant problem, but with ambiguity	2	Why were they built like that? (Prompt B)	
Relevant problem without any ambiguity	3	From just looking at the picture, how many circles can be calculated by each color? (Prompt A)	
Non-routine relevant problem without any ambiguity	4	If the real estate agency wanted to renovate and deduct 10 meters in the living room to give more space to both Terrace and kitchen, what would be the area of the Living room? (Prompt B)	
Non-routine relevant problem without any ambiguity; problem allows for multiple solutions	5	How do the color and space between each color make this picture pleasing to the eye? (Prompt A)	

problem is relevant to the prompt, whether the problem statement is ambiguous or not, and whether the problem allows for multiple solutions. An example problem with a complexity rating of 5 is in Table 2: How does the color and space between each color make this picture pleasing to the eye? This is a non-routine problem that usually does not exist in a math textbook, and there are multiple perspectives and strategies to answer this question. For instance, we could measure the distance between each circle, calculate the portion each circle is covered, explore the different shapes created by the set of circles, and check the RGB information of the colors to understand if any of these factors make the picture pleasing to the eye. Cohen's kappa (Cohen, 1960) was utilized to calculate the reliability of the content complexity coding manual. Notably, 54 problems were selected randomly from a total of 140 problems in three separate sets to be double-coded by the researcher and a second rater. The weighted kappa was 0.81, which is considered a good agreement (Landis and Koch, 1977).

We compared students' *mathematical dispositions* with their responses in the pre- and post-mathematical disposition surveys with a paired t-test. In total, there were 17 students who finished both the pre- and post-surveys (35 pre-survey, 18 post-survey). Next, a linear mixed-effects regression model was used to compare the *content complexity* of student-generated problems in different problem-posing activities. The model was fit with student ID as a random effect. Student characteristics (i.e., the pre-survey math interest, pre-test procedural fluency score, pre-test conceptual understanding score, pre-test problem-solving score, gender, and grade level) were tested for significance as covariates. The three problem-posing activities during the math walks program were also included in the model, along with the pre- and post-survey problem-posing tasks as covariates. In this model, each data point was one student creating one problem. In total, there were 261 student-created problems, including 134 video-watching activity problems, 44 #STEMlens photo problems, 30 Final Walk problems, 35 pre-survey problem-posing task problems, and 18 post-survey problem-posing task problems.

The linear mixed-effects model was fit using the linear mixed-effects regression (*lmer*) command from the *lme4* library in R (Bates et al., 2015; R Core Team, 2016). The mixed-effects model was selected as it allowed us to use all the data despite students completing different numbers and types of problem-posing tasks. It could also account for the partially clustered data.

The qualitative analysis portion of this study employed a single-case-study design (Creswell, 2013). The identified case in this study

TABLE 3 Descriptive statistics of all measures.

Variable name	*n*	*M*	SD
Pre-survey interest in mathematics	35	3.63	0.75
Post-survey interest in mathematics	18	3.88	0.64
Pre-survey posed problem content complexity	31	2.77	1.15
Post-survey posed problem content complexity	16	3.41	1.08
Video-based problems content complexity	18	3.13	0.20
#STEMlens content complexity	15	3.15	0.39
Final walk content complexity	12	3.83	0.33
Pre-test procedural fluency score	35	2.73	1.12
Pre-test conceptual understanding score	35	2.84	0.89
Pre-test problem-solving score	35	1.39	1.24

was the math walks program at the college preparation program. Thematic analysis was employed to identify and examine themes that emerged from the data following the six-phase procedure presented in Braun and Clarke (2006): familiarizing yourself with your data, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the report. In light of the findings in the pilot study described earlier, some potential coding foci that the researcher paid particular attention to are listed in Appendix E.

4. Results

Table 3 presents descriptive statistics for the measures. Due to the online format of this program and its implementation toward the beginning of the COVID-19 pandemic, the attrition rate was fairly high. There were 35 pre-survey responses and 17 post-responses. To understand if students who left the program were different from students who finished, the authors conducted an independent *t*-test on these two groups' pre-survey interest and pre-survey problem-posing complexity. The independent *t*-test result revealed that the difference in students' pre-survey dispositions was not statistically significant, $t\ (32) = -0.23$, 95% CI = [−0.54, 0.43], $p = 0.82$. However, the difference in students' pre-survey problem complexity was statistically significant, $t\ (34) = 3.67$, 95% CI = [0.69, 2.39], $p < 0.001$. In other words, there was not enough evidence that students who dropped off from the program had more positive or negative dispositions toward mathematics. However, students who stayed in the program were able to pose more complex problems from the beginning of the program than their counterparts.

The average complexity of student-generated problems in the pre- and post-survey and the different problem-posing learning tasks are included in rows 3–7 of Table 3. The data suggested that the average complexity of student-generated problems for the Final Walk was higher than the other two learning activities in the program (#STEMLens photos and walkSTEM videos). The average complexity of student-generated problems in the post-survey is also higher than in the pre-survey.

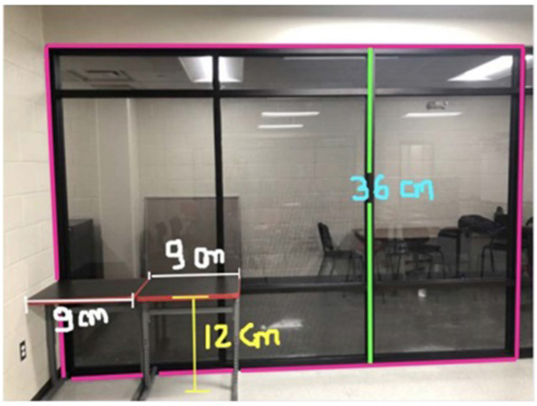


FIGURE 1
#STEMlens activity student work—The window. 1-How many tables do we need to fill the whole window? 2-How many rows are we going to create? 3-How many columns are we going to create?

4.1. RQ1: Students' dispositions toward mathematics and problem-posing

The Shapiro-Wilk's test for the difference between pre-survey and post-survey interest mean indicated that the difference was normally distributed ($p = 0.91$; Shapiro and Wilk, 1965). The test of homogeneity of variances indicated that the variances were not significantly different from each other, $F\ (1.32) = 0.15$, $p = 0.70$. The paired *t*-test result revealed that the improvement in students' interest from pre-survey to post-survey, 0.15, 95% CI [−0.10, 0.41], was *not* statistically significant, $t\ (16) = 1.28$, $p = 0.22$.

Following the quantitative analyses, we used thematic analysis to analyze the transcripts of the post-intervention student interviews, and the following themes emerged from the analysis.

Eight out of the 10 students being interviewed mentioned that they started to think more deeply and positively about mathematical concepts. One student (female, grade 10) explained as follows:

> [the program] actually gives you a reflection of yourself that you did not know. Because something as a student you just ask like, why would the teacher ask me this kind of question. And when you do this kind of project you actually understand what situation the teacher was in and why did she ask this question. … In this kind of program, I think you'll actually understand and have more, more understanding, and more clarification on questions.

TABLE 4 Mixed-effects linear regression model comparing problems' complexity—Pre-survey problem-posing task as reference group (No. of observations: 261).

Random effect	Variance		SD			
Student ID	0.44		0.66			
Fixed effects	*B*	d^a	*SE*	95%CI	*p*-value	Sig.
(Intercept)	0.97		1.41	[−1.80, 3.74]	0.50	
Pre-survey problem-posing task	(ref.)					
#STEMlens photo	0.70	0.99	0.19	[0.33, 1.08]	0.002	**
Final walk project	1.22	1.72	0.19	[0.85, 1.60]	<0.0001	* * *
Video-watching activity	0.37	0.52	0.16	[0.05, 0.69]	0.02	*
Post-survey problem-posing task	0.45	0.63	0.22	[0.006, 0.89]	0.048	*
Pre-survey math interest	0.06		0.26	[−0.46, 0.57]	0.83	
Pre-test procedural fluency score	0.11		0.16	[−0.20, 0.43]	0.50	
Pre-test conceptual understanding score	0.33		0.23	[−0.12, 0.79]	0.17	
Pre-test problem-solving score	0.04		0.18	[−0.30, 0.39]	0.79	
Gender female	(ref.)					
Gender male	−0.68	−0.96	0.33	[−1.33, −0.04]	0.05	*
9th Grade	(ref.)					
10th Grade	0.33	0.46	0.77	[−1.17, 1.83]	0.68	
11th Grade	−0.13	−0.19	0.84	[−1.77, 1.51]	0.88	
12th Grade	−0.03	−0.04	0.73	[−1.47, 1.41]	0.97	

Adjusted $R^2 = 0.58$, RMSE = 0.67.
[a]Cohen' *d* effect sizes are calculated with the *emmeans* package through estimated marginal means (Russell, 2023).
*indicates the correlation is significant at the.05 level (two-tailed), $p < 0.05$.
**indicates the correlation is significant at the.01 level (two-tailed), $p < 0.01$.
***indicates the correlation is significant at the.001 level (two-tailed), $p < 0.001$.

The same student also described her experience with the #STEMlens photo activity to further demonstrate a similar idea. The picture and questions she mentioned are presented in Figure 1.

> So one of the picture I took was the picture of my window. So I think, I like the creativity because when you create the question sometimes can't get that type of question… But I have multiple questions, I have other things we can actually put on the thing that were kind of complicated. So I was proud of myself because that makes me think I still remember I still have that kind of … the capacity, memory, how you can interpret real-life problems … I found myself asking questions that the teacher doesn't even ask.

Five students expressed that they became more interested in mathematics to some extent. One female student in grade 12 stated:

> Just slightly more it's not like I really got into math or I really got into science but I really like it increased my like interest on it. Just to think about like why doesn't it happen or how is this related with stuff that I've learned before but I've never paying attention to it.

Three students mentioned that they were more patient and perseverant when solving mathematical problems after the intervention. In this program, students were only required to solve their self-generated problems in the Final Walk project, and students' Final Walk problems were the most complex according to the coding manual. That is to say, students spontaneously chose to pose and solve problems that were more complex and required more effort to answer. Students described the problem-solving process here as research and highlighted that it was different from the textbook problems they were used to

> It was a good experience and then I get I got to learn more about it how it really is to do a research most importantly because I think it's good … it help me like think more about how they kind of research really goes and I mean, it's not a full research. It's not a full research but I got like a glimpse of it (female, grade 12).
>
> Yes, Because I think I learned more I gain more experience on how to solve stuff, having patience, because it can be hard at some point, but having patience, take it easy … we can find a solution (female, grade 12).

Thus, the quantitative and qualitative results were not consistent.

4.2. RQ2: The complexity of students' posed problems

The mixed-effects model was employed, and the regression results and Cohen's d-effect sizes are presented in Table 4. The effect sizes were calculated from the estimated marginal means with the estimated marginal means, aka least-squares means (*emmeans*) package in R (Russell, 2023). The regression results suggested that students' post-survey problems were more complex than pre-survey problems ($b = 0.45$, $p = 0.047$, $d = 0.63$). The results revealed that the Final Walk problems' complexity was significantly higher than all other problems. Final Walk problems were more complex than #STEMlens ($b = -0.52$, $p = 0.0006$, $d = -0.73$) video watching ($b = -0.85$, $p < 0.0001$, $d = -1.20$), post-survey ($b = -0.78$, $p = 0.0004$, $d = -1.10$), and pre-survey problems ($b = -1.22$, $p < 0.0001$, $d = -1.72$). On the other hand, the pre-survey problem complexity was significantly lower than all other problem complexities. In addition, the video-watching problems were less complex than the #STEMLens problems ($b = -0.33$, $p = 0.017$, $d = -0.47$). As introduced earlier, the Final Walk and #STEMlens activities were categorized as free problem-posing, and the video watching was considered semi-structured problem-posing, according to Stoyanova (1999). The results showed that students posed more complex problems in free problem-posing activities (i.e., Final Walk, #STEMlens) than in semi-structured problem-posing activities (i.e., video watching). All pairwise comparison results and corresponding effect sizes are presented in Figure 2.

One student's problem-posing work is presented in Table 5 to show the problems at different stages throughout the program. Eric was a 10th grader in the program with a pre-survey mathematical interest rating of 2.75 on a 5-point scale. Eric watched 14 walkSTEM videos and submitted 19 #STEMlens photos. We listed five video-watching problems, five #STEMlens problems, the Final Walk problems, and the pre- and post-survey problems that Eric posed in the table. The problems Eric created for the #STEMlens activity showed that he was able to pose more and more complex and creative problems about his surroundings. For example, #STEMlens #1, #2, #10, and #13 were all about geometry concepts and measurements. The first two problems were similar to textbook problems students were accustomed to solving and were less creative. However, the #10 and #13 problems did not directly ask for a measurement but focused on how the shape of the chip container could affect the volume and how the positions of the fan blades could affect the efficiency. In addition, another theme that emerged from his #STEMlens submissions was the number of photos and problems he was able to create in the same environment. Eric took 5 #STEMlens photos and created accompanying problems in his backyard, which demonstrated how he was able to see various STEM topics and problems in the surroundings.

4.3. RQ3: Students' interactions during the math walks program

We analyzed students' participation during the online meetings and identified one key type of interaction: students giving each other feedback and collaborating to create theme-based problems.

In the #STEMlens and the Final Walk problem-posing activities, students were asked to pose problems based on the provided rubrics (Appendix D). The rubrics only talked about the quality of the photos and the markups, and the connection between the problems and the photos. In these two activities, students mainly worked independently except for when they were asked to evaluate each other's problems and provide

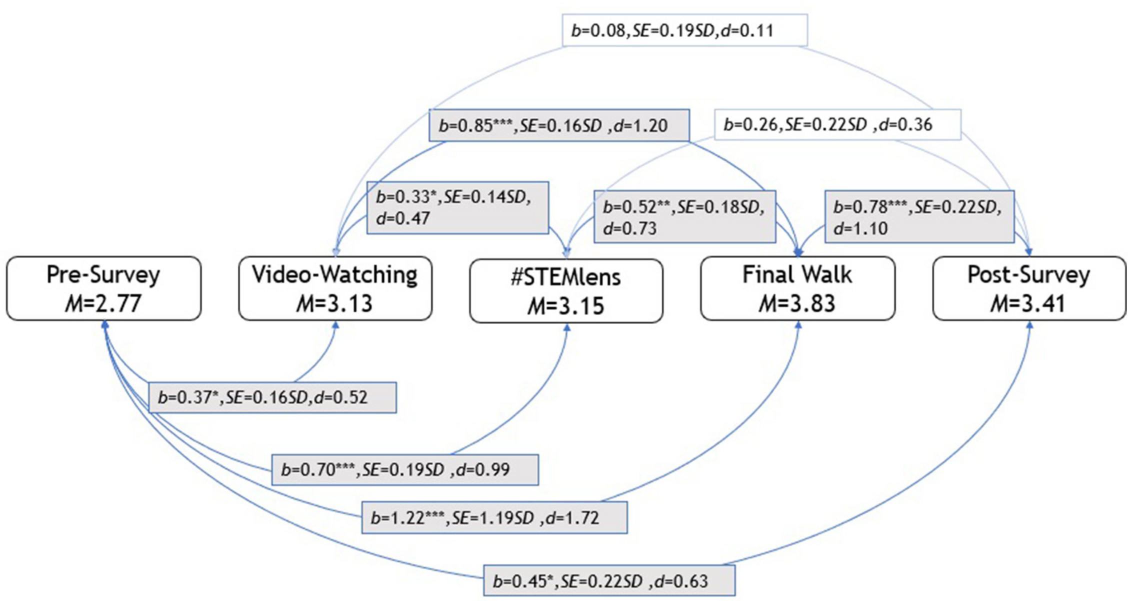
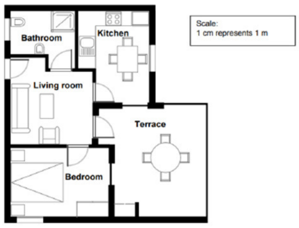
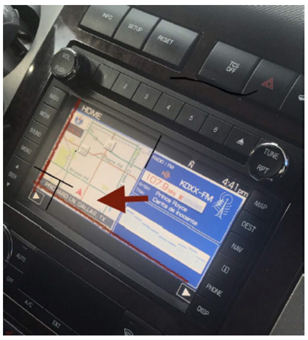


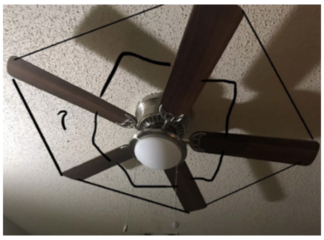
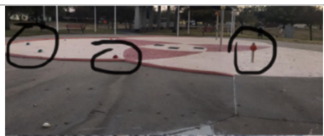
FIGURE 2
Pairwise comparison results of student—Generated problems.

TABLE 5 Eric's problem-posing work.

Activity	Problem-posing	
Pre-survey		From just looking at the picture, how many circles can be calculated by each color? What is the length of the bathroom and kitchen different from the length of the bedroom to the terrace by millimeters?
	 Pose a mathematical problem based on this apartment floor plan or this apartment	What type of measurement is used to determine that each part is equal? If I were to be on the other side of the globe and someone else was on the opposite side, would the time be the same?
Video-watching	talkSTEM Videos: https://youtu.be/5GCxIvRpKSA https://youtu.be/vg5AZEP-ZcE https://youtu.be/SJ4QwU_xSlg	How many toppings can I add to my drink? If 200 cells can fit on a top of a pen, how many cells does it take to run a whole mile? That is one of many bridges in Dallas. Can the same math be added to another bridge?
#STEMlens	Student submitted 19 #STEMlens photos.	
		#1: What is the radius and/or the diameter of this lamp's circular form?
		#2: What could be the area of the degree of the square-size tablet?
		#6: In my backyard, there is a huge tree, bigger than my house, and I have noticed that the smaller branches are usually pulled down because of the spider webs. Question: Does the size of the spider's web really affect how the smaller branches are pulled? And is the spider's webbing good enough to catch prey?

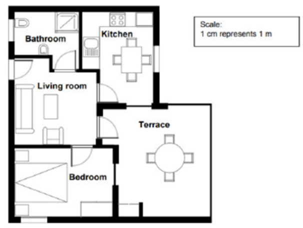
(Continued)

TABLE 5 (Continued)

Activity	Problem-posing	
		#8: From the picture, I have speculated that the wooden walls in the backyard are falling. Question: What would be the cause of the wood falling? Metal bars have been added to support it, but even so, they still fall. Is there a logical explanation for the wood getting weaker?
		#10: Can the size of the bag or box affect the amount of chips inside it? Or, to be more specific, can you say a cylindrical shape holds more chips than a box or a bag?
		#13: Do the fans work more effectively if they are far apart from each other to a certain degree?
Final walk	  I wonder why there are so many things to power one small water park, and what intrigues me is how it is used; it is useful for sanitization and other reasons. How much water was possibly used daily? Also, from the sign shown, what kind of chemicals were added to the water and for what reason?	
Post-survey		I see all of the circles on top of each other, and I would ask the question, What could the radius of all the circles be, and could they all be the same? I describe this picture as a way to figure out what the size of each circle could be. What could be the radius of each circle and are they all the same? From this picture, it makes me think about what could be the radius of each circle and which formula could help with that? And if each circle is the same size as each other

(Continued)

TABLE 5 (Continued)

Activity	Problem-posing	
	 Pose a mathematical problem based on this apartment floor plan or this apartment	What could be the cm of each room of this house, and how you turn it into an m? What is the volume of the whole house by comparing each room's size? What could be the length of the whole house considering each room of the house?

feedback. Their feedback mostly only talked about the two aspects of the rubric. Below is an example of one student (male, grade 12) who talked about another student's #STEMlens (Figure 3) submission.

> I will rate the question as a four I think. Because it is not that specific, it's just in the details. The markups, I think a four because you cannot see the complete image of the cone.

Once students became familiarized with problem-posing, they started to work on the Final Walk project. An added layer to this project compared to #STEMlens photos was the presence of a theme. Each group had to choose one theme, which could be a STEM topic, a place, or an interesting area. As a result, when students worked together in groups to create the Final Walk, they had to collaborate with each other to make sure their problems shared the same theme. In this excerpt, Abby (grade 12) started with a problem more related to geometry than biology, and she managed to modify her problem based on some feedback she received from Gina (grade 12) and the instructor. Abby's photo is presented in Figure 4. After this discussion, Abby modified here problem from "what is the space between the two branches" to "what caused the tree to grow in that shape or form? does it have to do with the soil?"

> Abby: My photo was a tree like a tree branch in the form of a triangle. And I was going to ask, what is the space between both of the branches if I'm given a squared plus b squared equals c squared?
>
> Instructor: So I guess my question to you is, would that be more related to biology or geometry with that question?
>
> Abby: Geometry.
>
> Instructor: Geometry, because you're talking about Pythagorean Theorem, a squared plus b squared plus c squared. So you kind of want to think about it in a more biological lens, if that makes sense. So other than Aurora, thank you for sharing, Jennifer and Nathalie. Anybody? What kind of questions can we ask about a tree that is in a that forms a triangle? What kind of questions we ask about it from a biological or environmental science lens, rather than a lens of geometry?
>
> Gina: Maybe why the tree took that form? Like is there something else? Like if it got trapped between something or just why does it has that shape?

In this online program, students were not able to collaborate with each other in the same ways as they usually do in in-person meetings. Naturally, the peer collaboration rate decreased significantly as some students did not even turn on their cameras. However, once students started to work on the Final Walk project, they were more likely to critique each other's problems and discuss how they could pose different problems so that their problems could be integrated into a theme-based walk. In this online program, the Final Walk project was implemented last and fewer students participated in this Final Walk project than the #STEMlens activity due to the high attrition rate. However, instances in which students collaboratively pose problems only occurred during the Final Walk project. The two examples above showed how students interacted differently when evaluating their peers' problem-posing work in #STEMlens and the Final Walk project. In the first example, the student's comment only focused on the criteria in the #STEMlens rubric (e.g., the markup and the clearness of the photo). However, in the second excerpt, Gina proposed some new ideas and questions about the tree in Abby's photo, and Abby was able to connect her question to the group's theme (i.e., biology and environmental science) with Gina's suggestion.

5. Discussion

According to our quantitative analyses that investigated students' mathematical dispositions, there was not enough evidence to conclude that math walk activities enhanced dispositions. One explanation for this insignificant result is the small sample size. A recent meta-analysis calculated the average weighted effect size of students' dispositions after attending problem-posing interventions and reported an effect size of 0.54 (Wang et al., 2022). According to the power analysis with G*Power (Faul et al., 2009), in order to compare students' dispositions between two dependent means, the total sample size should be equal to or greater than 47. However, in this study, the sample size between pre-survey and post-survey mathematical disposition was 17, which made this analysis underpowered. On the other hand, the qualitative analyses revealed three themes related to how students were able to think differently and deeper about mathematical concepts, be more interested in mathematics, and be more perseverant in solving problems. However, these effects may not have shown up in the interests

FIGURE 3
#STEMlens activity student work—The birthday hat.


FIGURE 4
Abby's final work problem photo. Problem: what caused the tree to grow in that shape or form? Does it have to do with doil?

survey if students still saw math walks as being disconnected from "school math."

As introduced earlier, students participated in both semi-structured and free problem-posing. The results suggested that students were able to pose more complex problems by the end of the program in the post-survey than in the pre-survey, which validated the positive effect of this online program. In addition, students posed more complex problems in the Final Walk project than in the video-watching activities and the pre- and post-survey, which resonated with the finding from the meta-analysis introduced earlier (Wang et al., 2022) that including free problem-posing tasks could increase students' performance. However, the results also indicated that even though both #STEMlens and Final Walk were free problem-posing tasks, the problems students generated in the #STEMlens activity were significantly less complicated than the Final Walk problems. The main difference between the #STEMlens and Final Walk project was the peer collaboration and the presentation. Students were able to collaborate as a group, review each other's problems, provide feedback, and solve the problems together in the Final Walk, which may have promoted more problem complexity.

In short, students tended to pose more complex problems in a free problem-posing task than in a semi-structured problem-posing task. Moreover, collaborating with peers to pose and solve problems and the requirement to present the problems to the audience also was associated with more complex problems. This result provides evidence for the authentic audience effect discussed in Crespo (2003): Introducing an authentic audience (e.g., sharing student-generated problems with others to solve) could motivate students' active participation in problem-posing.

5.1. Limitations and future directions

The limitations of this study were discussed from three perspectives. First, when generalizing the research findings to other students or other problem-posing interventions, caution should be taken. All of the meetings in this program were delivered through virtual online meetings. In addition, this program was implemented during a pandemic, and the majority of the students were already attending online classes all day from home. As a result, it could be difficult for students to be fully engaged in all of the activities and meetings, and the instructors were not able to monitor students' learning progress. Second, the small sample size was relatively small for quantitative analyses. As suggested above, these were the challenges and limitations caused by the online format and the special time of the program. The researchers employed this mixed-method research design and used various data sources to triangulate the findings and results to address this limitation. Finally, we acknowledge that our positionalities (as an international doctoral student and a faculty member interested in mathematics education and problem-posing) impact analyzing data and interpreting results and findings in this study.

This study tested and established the possibility of implementing a purely online math walks program. In prior studies, math walks were mostly implemented through in-person programs where children and youth meet with their facilitators at the learning sites (Lancaster, 2021; Wang et al., 2021; Martínez-Jiménez et al., 2022). This study provided future researchers with some insights about implementing a completely virtual math walks program. When designing and implementing online programs, future researchers should especially pay attention to developing collaborative activities to increase participant engagement and peer interaction levels. These collaborative activities are not only effective scaffolding strategies to support students' learning activities but can also potentially address the high attrition issue with online programs. These research findings also provide educators who are interested in implementing problem-posing with their students an easy-to-administer plan for afterschool programs or other informal learning environments. This study gives an idea of the kinds of interactions and problem characteristics to look for, as well as the ways in which such a program might effect or not effect outcomes that educators are interested in. Although this online program was implemented with high school students, the pilot study published by Wang et al. (2021) explored how a math walk could be administered to early elementary students. Hence, multiple different age ranges are possible. In addition, future research should investigate the students' performance in different types of math walks tasks on a large scale and explore how to use the different math walk tasks to develop a more student-friendly, personalized, and interactive program for youth. Moreover, in this study, the quantitative results on students' problem-posing indicated no significant difference in students' mathematical disposition. However, the qualitative analysis results revealed that students were able to think differently and deeper about mathematical concepts and became more interested in problem-posing. Hence, future researchers can employ more targeted measures, such as the attitudes toward problem-posing (ATPP) questionnaire from Nedaei et al. (2019), to better capture the change in students' dispositions toward problem-posing. In addition, some extant literature has investigated students' problem-posing performance by responding to different problem-posing prompts. Zhang et al. (2022) analyzed 669 elementary school students' problem-posing work and concluded that students performed better in problem-posing tasks with specific numerical information than in tasks without numerical information. Future research should investigate how different types of problem-posing prompts and programs can affect students' problem-posing work and behaviors. Finally, increasing levels of problem complexity seem to signal deeper thinking about mathematics but can be highly task specific. Future research should examine methods for having students pose authentic and community-imbedded problems.

6. Conclusion

This study employed a mixed-method research design to investigate an online math walks program's effects on students' mathematical dispositions and problem-posing performance. The online math walks program created an informal STEM learning environment for youth and engaged them in a series of problem-posing activities. The results partially validated how the math walk informal learning environment and the problem-posing activities youth participated in influenced youth to develop more positive mathematical learning dispositions. Through posing problems in their homes and communities, youth were able to think deeper and differently about mathematical concepts and make connections between school math and real-world applications. This study also compared youth's problem-posing work in different learning activities. It concluded that youth posed more complex problems in free problem-posing tasks when they were instructed to collaborate with each other to create problems and present their self-generated problems to the audience.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Southern Methodist University Institutional Review Board. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin. Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

Author contributions

Both authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Informal STEM learning: Examples from everyday spatial behaviors

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Introduction: Extensive research has shown a close relationship between spatial abilities and success in STEM disciplines because many STEM problems often require students to reason about spatial information. Everyday spatial behaviors may predate and facilitate the development of spatial skills. Therefore, the current study examined children's everyday spatial behaviors and their associations with broader child development outcomes and individual differences.

Methods: Based on previous research, we developed an everyday spatial behaviors questionnaire for children (ESBQC). A total of 174 parents and their children aged 4–9 years old participated. In ESBQC, parents rated how much difficulty their children experience with different spatial behaviors, such as putting together a puzzle, retracing a route, or hitting a moving ball.

Results: Factor analysis revealed 8 components in ESBQC. The internal reliabilities were relatively high. ESBQC was positively correlated with age but not with sex. Furthermore, ESBQC predicted sense of direction, even after considering age and bias associated with parent reports.

Discussion: Our questionnaire may provide a useful tool for parents and other stakeholders to better understand everyday spatial behaviors and encourage interest and competence in spatial skills, ultimately promoting STEM learning in informal, everyday settings.

KEYWORDS

informal STEM learning, everyday spatial behavior, children, sense of direction, adaptive living, sex difference, age difference

Introduction

The United States is facing an ever-increasing demand for talent in STEM fields (science, technology, engineering, and mathematics, U.S. Bureau of Labor Statistics, 2022). However, fewer students than needed are pursuing certain STEM majors and careers (Xue and Larson, 2015). Furthermore, many K-12 students (as high as 30%–40%) are not meeting national STEM content standards (U.S. Department of Education, 2019). Therefore, there is an urgent need to increase STEM competency and the number of people going into STEM fields. STEM interests and identities can and should be fostered early in child development (Perez et al., 2014; Dou et al., 2019), with STEM learning occurring in formal school settings and informal settings outside of school (Alexandre et al., 2022). Researching informal STEM learning is particularly critical, considering that children spend 80% of their time outside school (Meltzoff et al., 2009). The current study examined 4–9-year-olds' informal STEM-related activities through parent reports of everyday spatial behaviors.

Spatial abilities and everyday spatial behaviors

Spatial abilities refer to representing, manipulating, and remembering the visual–spatial relations among objects or space. People perform spatial behaviors every day, which commonly draw on spatial abilities. For instance, a common spatial behavior, such as putting together a puzzle, may involve the spatial abilities of spatial perception and mental rotation. Everyday spatial behaviors can be examined *via* questionnaires. For instance, Newcombe et al. (1983) asked college students to rate how often (1: never, 6: more than once a week) they participated in several spatial activities, such as basketball, bowling, tap dancing, navigating in a car, interior decorating, and fixing radios (also see Signorella et al., 1986; Voyer et al., 2000). However, this line of studies focused on one's preference for spatial activities rather than competence in these spatial activities/behaviors.

Eliot and Czarnolewski (2007) designed an Everyday Spatial Behavioral Questionnaire (ESBQ) focusing on spatial competence. College students were asked to rate how often they found each activity difficult to perform. There were 116 everyday spatial activities. Factor analyses revealed 12 subscales, including object capacity, estimating covering, estimating distance, estimating direction, reversals, accurate drawing, spatial movement, driving, spatial memory, disembedding, assembling objects, and judging relationships. Canonical correlation analyses with age, sex, and different spatial tests (e.g., hidden figures) revealed two latent characteristic roots: moving through space (e.g., driving, walking) and 3-dimensional visualization. Furthermore, some spatial tests (i.e., Hidden Figures, Maze tracing test) loaded on the same characteristic root as some subscales of ESBQ. Although, some other spatial tests (i.e., Gestalt completion, Card rotation) did not.

Lawton et al. (2015) later revised the ESBQ by adding more items about movement in space (grasping vs. distance action space) and removing other items, resulting in a total of 132 items. They found 12 subscales with slightly different namings: relating objects to earth-fixed axes, movement in proximal space, navigation/orientation, fitting, driving, disembedding/targeting in proximal space, spatial relations in pictures, horizontality/verticality in proximal space, overlaying/covering space, distance/area relations, moving objects in proximal space, and following dance instructions/drawing in proportion. They also found sex differences. Women perceived some activities (e.g., relating objects to earth-fixed axes, movement in proximal space, driving, and navigation) to be more difficult than men did, but they perceived some other activities (e.g., overlaying/covering space, fitting, following dance instructions, and drawing in proportion) to be less difficult. This series of ESBQ questionnaires is instrumental in measuring competency in a variety of everyday spatial behaviors. However, these studies focused exclusively on adults. It is still unknown how competent children are at everyday spatial behaviors, how competence in everyday spatial behaviors goes through development during childhood, and their associated individual differences.

The importance of spatial abilities and behaviors for children

Almost 70 years of research has solidified that spatial abilities are critical for developing expertise in STEM fields (Super and Bachrach, 1957; Wai et al., 2009). Project Talent, a longitudinal study tracking adolescence into adulthood, found that the likelihood of obtaining advanced STEM degrees increases as a function of spatial ability during adolescence (Wai et al., 2009). Many STEM fields depend greatly on spatial thinking and reasoning. For instance, geology may require students to mentally transform rock layers to understand how the mountain takes the shape they do (Uttal and Cohen, 2012). The field of biology may require students to understand the spatial structures of protein molecules. For many abstract scientific phenomena and concepts, students also need to comprehend and describe graphs, diagrams, and physical models which reflect visual–spatial representations. Therefore, competence in spatial thinking and reasoning may help to increase STEM success and the number of people going into STEM fields (Uttal and Cohen, 2012; Stieff and Uttal, 2015). However, unlike mathematics and verbal abilities, which are also important predictors of STEM success and formally taught at school, spatial abilities have received much less attention in the K-12 school curriculum (Kell and Lubinski, 2013).

Studying everyday spatial behaviors may open a window for us to better identify opportunities to engage and promote spatial abilities in children's daily lives. Many studies have supported this proposition. For instance, Schug et al. (2022) found that playing with Legos in childhood predicted better performance on mental rotation tasks in adults. Similarly, Jirout and Newcombe (2015) found that parent reports of children playing with puzzles, blocks, and board games positively predicted children's performance on the Block Design test on the WPPSI-IV (Wechsler Preschool & Primary Scale of Intelligence) for children whose parents reported they played often. Some experimental studies focusing on spatial language also lent strong support for the causal relationship between spatial experience and spatial cognition. For instance, Casasola et al. (2020) found that engaging in spatial language during play could improve children's mental rotation performance relative to the control condition with little spatial language. A series of naturalistic, museum studies also corroborate that conversations and constructive plays, typically elicited by parents and learned by children, could help improve children's performance on a variety of spatial tasks (Haden et al., 2014; Polinsky et al., 2017; Pagano et al., 2019). Considering the important role of spatial behaviors in spatial development, it is therefore critical to examine daily spatial behaviors in children.

Current study

Increased competence and interest in everyday spatial behaviors may ultimately engage, motivate, and promote spatial abilities as well as STEM learning and readiness (Katz, 2011; Leyva et al., 2021). For instance, the common spatial behaviors of putting together puzzle pieces or assembling furniture encourage spatial thinking and reasoning. These types of spatial thinking and reasoning are relevant to many STEM problems, such as understanding the structures of DNA and atoms. However, few studies have examined everyday spatial behaviors in children, especially young children who have just started formal learning of spatial concepts such as maps. Several studies have probed a series of informal STEM-related activities (Ramani et al., 2015; Zucker et al., 2021; Hightower et al., 2022) and included certain spatial-related items (e.g., talking about shapes, playing with blocks), but did not focus on spatial behaviors exclusively.

Many studies that had examined everyday spatial behaviors comprehensively only examined college students (Eliot and Czarnolewski, 2007; Lawton et al., 2015). A few have examined childhood spatial activities but have used retrospective reports from adults, which is prone to recall bias (Lawton and Kallai, 2002; Vieites et al., 2020; Schug et al., 2022). Therefore, the current study aimed to fill this gap and investigate parent reports of everyday spatial behaviors in children aged 4–9 years old in order to examine informal STEM-related activities during early childhood. Parent reports such as the one used here have been increasingly used to examine cognitive development. For instance, Yang et al. (2018) found parents reported that their children with intellectual disabilities (i.e., Down Syndrome) with a mental age of 4–9 years old have few wayfinding skills but much confidence. Hence, children's limited metacognitive abilities (Salles et al., 2016) can make parent reports a highly useful tool to investigate everyday spatial behaviors. Furthermore, parent reports take less time and resources than observation-based studies and can examine multiple and diverse spatial behaviors of children in one setting.

Studying everyday spatial behaviors may help demonstrate to parents and other stakeholders that many real life behaviors involve spatial skills and these everyday spatial behaviors may be a fertile ground for spatial concepts and skills to germinate in children. In fact, many parents may not realize that children can develop cognitive skills and learn science during play and daily activities (Gomes and Fleer, 2019). Studying everyday spatial behaviors in children may also contribute to understanding individual differences in spatial abilities. Spatial ability is one domain where researchers have found relatively strong evidence of sex differences indicating a male strength (Johnson and Meade, 1987). However, the origin, cause, and development of these sex differences are still under debate (e.g., Levine et al., 2005; Newcombe, 2020; Rahe and Jansen, 2022). Vieites et al. (2020) found that childhood wayfinding experience (e.g., distance traveled) could mediate sex differences in some wayfinding strategies (i.e., route, but not survey) and anxiety in adults (also see Lawton and Kallai, 2002; Schug et al., 2022). Therefore, studying spatial behaviors in children may help understand whether vast individual differences observed for many spatial abilities also extend to everyday spatial behaviors. This knowledge may help identify the behavioral precursors of individual differences in spatial abilities in adults and inform training programs to improve spatial abilities and STEM-related competence (Stieff and Uttal, 2015).

In the current study, parents were asked whether their children were competent in a series of everyday spatial behaviors. To situate everyday spatial behaviors in a broader developmental context, we also examined the relationship between everyday spatial behaviors and other childhood outcomes, including adaptive behaviors, cognitive ability, and sense of direction. Lastly, we examined age- and sex-related individual differences to determine whether increasing age was associated with increasing competence in everyday spatial behaviors and whether boys and girls differed.

Methods

Participants

This study was part of a larger study that examined spatial abilities and behaviors in developmental populations. A total of 174 children aged 4–9 years old (97 boys and 77 girls) completed a series of cognitive and behavioral tests. All but one was free of any intellectual or developmental disabilities as reported by their parents (see results section). One parent identified their child as having Autism. Their data are included because removing or keeping their data did not impact the pattern of results. For more detailed information about age and sex composition, please see Table 1. One parent of each child participant completed the questionnaires. There were two testing modalities: in person vs. online. Earlier participants (65 children and 65 parents) completed the study in person. Due to Covid, later participants (109 children and 109 parents) completed the study online. Differences between the two modalities are discussed in the results section. Participants were recruited through listservs, local programs (e.g., afterschool programs, street fairs), social media (e.g., Facebook, Instagram, *ChildrenHelpingScience.com*), and lists of previous participants. In-person participants received a $40 Amazon gift card. Online participants received a $50 Amazon gift card because of longer sessions. All the recruitment and testing procedures followed the ethical guidelines of the university.

General measures and procedures

Parents completed a demographic questionnaire (about their children's age, sex, and presence/absence of intellectual/developmental disabilities), Everyday Spatial Behavior Questionnaire for Children (ESBQC), Santa Barbara Sense of Direction Scale (SBSOD), and Vineland Adaptive Behavior Scales (Vineland-3), in that order. All the questionnaires were presented online *via* Qualtrics. For in-person testing, parents completed the questionnaires independently on a computer in a quiet lab room, while their children completed the testing in a separate room with one or two researchers. For online testing, parents completed the questionnaires on their own time before their children started the testing with the researchers over zoom. Children completed a series of cognitive and behavioral measures. They always completed the Raven's Progressive Matrices test (Raven's 2) first. Only Raven's 2 from the child measures was used here.

Parent measures

ESBQC

To build the ESBQC, we first obtained the 36 items from ESBQ published in Lawton et al. (2015). We removed items inappropriate for children, such as those related to driving and parking. Three trained research assistants worked independently and collaboratively

TABLE 1 Sex and age distribution of child participants.

Age group	*N*	# of Males	# of Females	Mean (age)	SD (age)
4.00–4.99	32	15	17	4.51	0.30
5.00–5.99	41	27	14	5.49	0.28
6.00–6.99	23	13	10	6.49	0.32
7.00–7.99	23	13	10	7.50	0.29
8.00–8.99	23	12	11	8.51	0.29
9.00–9.99	32	17	15	9.55	0.27

to generate 31 new items. These newly generated items were similar to the original items and also complemented the existing ones. For instance, in Lawton et al. (2015), one item is "folding laundry" and we generated a similar item of "making a bed (i.e., evenly spreading sheets over the mattress)." Based on two items about ball-related sports (e.g., "Hitting an easily tossed ball with a bat or racket," Lawton et al., 2015), we generated several similar items such as "Catching a ball someone has thrown at them." One item in Lawton et al. (2015) is "Retracing a route backwards through an unfamiliar city." Based on this item, we expanded it into three items related to navigation:

1. *Retracting a route backwards through an unfamiliar place (e.g., the parked car on an unfamiliar playground)*
2. *Retracting a route backwards through an unfamiliar place (e.g., the entrance of an unfamiliar mall)*
3. *Retracting a route backwards through a familiar place (e.g., retracing their steps back to the front door in a familiar store or house)*

Among these three items, the first is about navigation in unfamiliar outdoor environments, the second is about navigation in unfamiliar indoor environments, and the third is navigation in familiar environments. Previous research has found that spatial navigation is different in different environments for children (Yang et al., 2022).

Extensive discussions were carried out to ensure that these items (1) were appropriate for our participants, (2) reflected common, everyday spatial behaviors, and (3) complemented the existing items. The reading level of all items was chosen to be at an 8th-grade level, confirmed through readability tests. One parent of a 5-year-old was invited to pilot test ESBQC for reading level, ambiguity, and appropriateness. The ESBQC final version consists of 52 items. Among them, 46 items are appropriate for children between 4 and 9 years old. There were 6 unique items for adolescents and adults with intellectual and developmental disabilities, which are not used in this study.

Parents were given the following instructions, slightly modified from the original ESBQ adult version (Eliot and Czarnolewski, 2007; Lawton et al., 2015).

> Please rate the perceived difficulty of the behaviors listed below based on your child's prior experience with the behaviors or similar behaviors. If your child has not engaged in one of the behaviors listed, imagine how difficult your child would find the activity based on their ability with other, similar activities. Please indicate whether your child always, very often, sometimes, rarely, or never has difficulties with these behaviors by clicking the button that corresponds to each answer.

Their rating was on a 5-point Likert Scale (1: always difficult; 5: never difficult). See Table 2 for all the items.

SBSOD

SBSOD (Hegarty et al., 2002) is a self-report measure of environmental ability or sense of direction. The scale contains 15 items, has been standardized and has good validity and reliability. We modified the wording, and parents rated their children's sense of direction on a 7-point Likert scale (1: Strongly agree; 7: Strongly disagree). For instance, we changed the original item of "I am very good at giving directions" to the modified item of "They are very good at giving directions." We reverse-coded items when needed so that higher scores indicated a better sense of direction. Total scores were obtained as outcome measures.

Vineland-3

Vineland-3 Comprehensive Parent/Caregiver form (Sparrow et al., 2016) measures adaptive behaviors based on 4 domains: Communication, Daily Living Skills, Socialization, and Motor Skills. This measure has been normed and standardized, has good reliability and validity, and is suitable for participants ages birth-90 years old. Parents were asked to rate their child's ability to perform each behavior without help. The Vineland Adaptive Behavior Composite (ABC) scores were obtained as outcome measures.

Child measures

Raven's 2 (Raven, 2018) is a nonverbal test that measures general cognitive abilities. The test has been normed and standardized, has good reliability and validity, and is suitable for participants ages 4–90 years old. In each trial, child participants needed to detect a pattern among several figures and choose the correct answer. The total raw scores were obtained as outcome measures.

Results

One parent scored the same responses (i.e., 5) for over 95% of all the questions in ESBQC. However, removing their data did not significantly alter the pattern of the results. Therefore, results were reported based on the entire sample. Some parents or their children did not finish all the questionnaires or Raven's 2. Their data were included whenever possible. A total of 162 parents and their children have completed all measures.

Descriptive analysis

We first conducted a descriptive analysis of the 46 items on ESBQC. The mean of each item ranged from 1.91 to 4.45. SD ranged from 1.32 to 0.69. The skewnesses of all items were all between +/−1, except for two items (picking out pennies from a pile of other change, −1.1, and telling which of two objects in the room is closer, −1.2; i.e., both left-skewed). The kurtoses of all items were all between +/−1, except for one item (telling which of two objects in the room is closer, 1.24, i.e., leptokurtic).

Among the 46 items, the 3 lowest rated (i.e., most difficult) items were:

Judging where North is in an unfamiliar playground ($M = 1.91$)

Retracing a route backwards through an unfamiliar place (e.g., the entrance of an unfamiliar mall; $M = 2.96$)

Swatting a fly ($M = 3.16$)

The 3 highest rated items (i.e., least difficult) were:

Judging whether the corner of an object is square ($M = 4.3$)

Walking through a doorway without knocking against it ($M = 4.44$)

Being able to tell which of two objects in the room is closer to them ($M = 4.45$)

TABLE 2 Pattern matrix based on the principal component analysis.

	Component							
	1	2	3	4	5	6	7	8
Touching a smudge on their face while looking in the mirror	0.724							
Judging whether a hole is vertical	0.620							
Being able to tell which of two objects in the room is closer to them	0.542							
Ability to judge if water will spill out of a glass when tilted	0.541							
Deciding whether they have drawn a perfectly horizontal line on a blank piece of paper	0.514							
Moving their left or right hand when told to do so	0.510							
Rotating an object that they are carrying (i.e., a large box or wide toy) so that it can fit through a smaller door	0.465							
Estimating how far apart two outdoor places are from each other (i.e., how far is the store from the car or the playground from the school)	0.451							
Deciding whether a cut out shape will fit into a hold (i.e., is the shape the right size to fit the hole)	0.434							
Judging whether a picture is straight when hung on a wall	0.418							
Kicking a ball that was kicked toward them (e.g., kicking a soccer ball)		0.851						
Hitting an easily tossed ball with a bat or racket		0.829						
Catching a ball someone has thrown at them		0.818						
Identifying where a ball will land if it has been dropped from a ladder		0.530						
Correctly running toward a spot where they anticipate a ball will land after it has been thrown from a distance		0.478						
Swatting a fly		0.456						
Following a dance step as in square dancing			−0.631					
Follow dance moves from someone who is facing them (i.e., moving their right arm for a dance move even though it looks like the instructor is moving their left hand since they are facing them)			−0.606					
Pointing to the right-hand side of the person facing them			−0.500					
Walking through a doorway without knocking against it			0.451					
Finding a pen on a crowded surface (e.g., desk or table)				0.835				
Finding one object among many (e.g., a Lego among blocks or a coin among leaves)				0.792				
Helping another person find their glasses or keys				0.757				
Ability to pick out pennies from a pile of other change				0.563				
Making a bed (i.e., evenly spreading sheets over the mattress)					0.594			
loading the dishwasher (or placing dishes in a drying rack)					0.558			
Retracting a route backwards through an unfamiliar place (e.g., the parked car on an unfamiliar playground)						−0.882		
Retracting a route backwards through an unfamiliar place (e.g., the entrance of an unfamiliar mall)						−0.868		
Retracting a route backwards through a familiar place (i.e., retracing their steps back to the front door in a familiar store or house)						−0.592		0.401
Drawing objects proportionately to each other in a picture (e.g., a big house, a tree and smaller people)							0.779	
Writing inside the lines on lined notebook paper							0.754	
Drawing a person so that parts of their body are in proportion							0.656	
Drawing a 5-pointed star							0.541	
Folding a piece of paper into equal halves							0.500	

(Continued)

TABLE 2 (Continued)

	Component							
	1	2	3	4	5	6	7	8
judging whether a chair is low enough to fit under a table								0.629
Deciding whether an article of clothing will fit without trying it on								0.463
Judging where North is in an unfamiliar playground								−0.410
Judging whether the corner of an object is square								
Estimating how far apart two objects are on a table								
Judging whether one thing is in front of another in a picture								
Assembling blocks or Legos to match a picture of blacks or Legos that have already been assembled								
Put puzzle pieces together								
Packing a bag or suitcase so that the bag can zip shut or putting toys in the toy box so that the lid can close								
Identifying landmarks that lead to home (i.e., a street sign or tree indicating that they are close to home)								
Using hallway signs and pictures to find their classroom at school								
Using signs or pictures to find a familiar place such as an aisle in the grocery store								
Eigenvalues (Initial)	17.453	3.026	2.402	1.670	1.622	1.402	1.122	1.064
% of variances (after rotation)	10.943	6.731	2.774	8.899	3.838	9.120	9.878	3.947
Reliability (alpha)	0.9	0.86	0.72	0.81	0.71	0.82	0.9	0.58

Factor loadings were ordered from the largest to the smallest for each factor. For ease of reading, only absolute values of coefficients over 0.40 are displayed.

Exploratory factor analysis of ESBQC

A principal component analysis was conducted on the 46 total items with oblique rotation (Oblimin with Kaiser Normalization) in SPSS 26. The Kaiser-Meyer-Olkin measure verified the sampling adequacy for the analysis, KMO = 0.912 (Field, 2013). All KMO values for individual items were >0.78, which is well above the acceptable limit of 0.5. Bartlet's test of sphericity χ^2 (1035) = 5185.19, $p < 0.001$, indicating that the correlations between items were sufficiently large for the analysis.

The principal component analysis yielded 8 components with eigenvalues over Kaiser's criterion of 1 and explained 64.70% of the variance in combination. See Table 1 for the pattern matrix. Only coefficients over 0.40 were displayed. We also performed reliability for each factor and the results are also listed in Table 2. We interpreted each component based on previous theoretical frameworks on categorizing spatial abilities (Lohman et al., 1987; Carroll, 1993; Montello, 1993; Newcombe and Shipley, 2015). The first component (10 items) was mainly about spatial perception in proximal space. The second component (6 items) was mainly about sports-related activities. The third component (4 items) was mainly about bodily spatial awareness. The fourth component (4 items) was mainly about spatial visual search. The fifth component (2 items) was mainly about fitting (e.g., making a bed). The sixth component (3 items) was mainly navigation. The seventh component (5 items) was mainly about drawing in proportion. The eighth component (4 items) was a mix of navigation, fitting, and spatial perception. All components except the eighth demonstrate acceptable reliability, >0.70. There were 9 items that did not have factor loadings over 0.40 on any of the component. One item (retracting a route backwards through a familiar place) loaded on components 6 and 8. We removed all the items that did not load on any components and all the items on component 8 due to low reliability. This resulted in a total of 34 items. We obtained the average score of these 34 items and analyzed its relations to other variables we collected.

Relationships with age, sex, SBSOD, and vineland

Next, we explored the relationship between ESBQC and modality, age, sex, SBSOD, Raven's and Vineland. See Table 3. ESBQC significantly correlated with modality, age, SBSOD, Raven's, and Vineland. The correlation strengths were moderate to large for all the significant correlations except for the one with modality (i.e., small). SBSOD was not correlated with sex, suggesting no sex differences between boys and girls in their parents' reports of their everyday spatial behaviors. Modality was significant such that ratings were higher in person ($M = 3.83$, SD = 0.59) than online ($M = 3.59$, SD = 0.59). See Figure 1 for a scatterplot of ESBQC as a function of age. It showed that competency in everyday spatial behaviors develops as a function of age. There were also wide individual differences in each age group.

Next, we conducted a hierarchical linear regression analysis to examine the validity of ESBQC. First, we examined whether ESBQC could predict SBSOD, which measures spatial ability in large-scale environments. We entered age in the first step. Sex and modality were not entered because their zero-order correlations with SBSOD were not significant. In step 2, we entered Vineland. Vineland is not designed specifically to measure spatial abilities but adaptive behaviors

TABLE 3 Pearson correlations between variables (sample sizes varied from 162 to 174).

	Age	Modality	Sex	Raven's	Vineland	SBSOD
ESBQC	0.553**	0.199**	−0.065	0.390**	0.469**	0.483**
Age	1	−0.089	0.032	0.676**	0.204**	0.156*
Modality		1	−0.042	−0.118	0.044	0.144
Sex			1	0.103	−0.190*	0.130
Ravens'				1	0.245**	0.156*
Vineland					1	0.365**

$p^* < 0.05$. $p^{**} < 0.001$. Sex: 0: girls, 1: boys. Modality: 0: online; 1: in person.

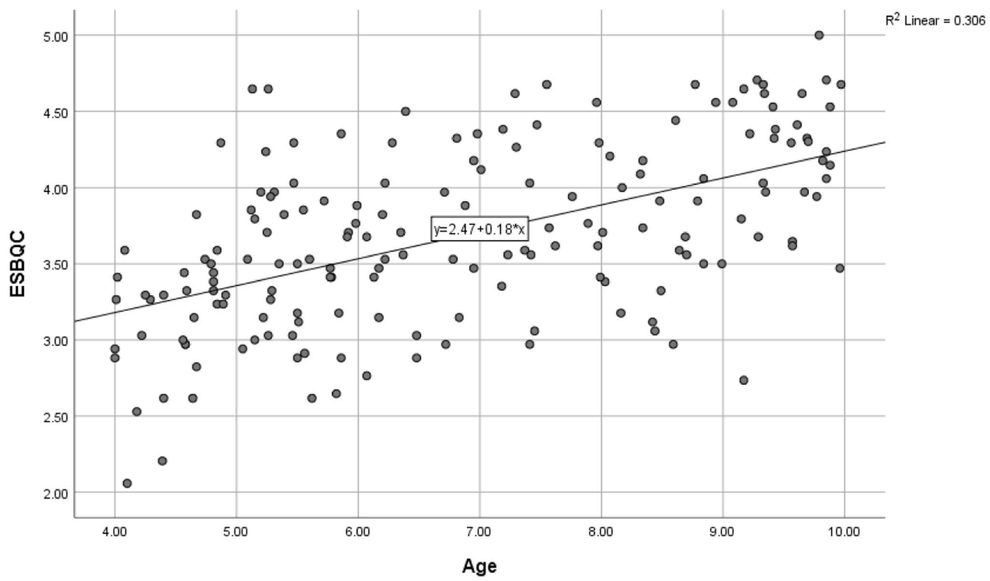

FIGURE 1
ESBQC as a function of age.

TABLE 4 Regression results on SBSOD.

Variables	β	t	Sig.	R^2	ΔR^2	F
Step 1				0.021		$F(1,163) = 3.48, p = 0.064$
Age	0.145	1.865	0.064			
Step 2				0.138	0.117**	$F(2,162) = 13.00, p < 0.001$
Age	0.073	0.981	0.328			
Vineland	0.350	4.699	0.000			
Step 3				0.265	0.127**	$F(3,161) = 19.36, p < 0.001$
Age	−0.148	−1.831	0.069			
Vineland	0.174	2.272	0.024			
ESBQC	0.472	5.269	0.000			

$^{**}p < 0.01$. Criterion (dependent) variable: SBSOD.

instead. However, it is also a questionnaire that parents completed. If parents have an overall tendency to answer similarly for all questions about their children, such as deeming their children capable of all sorts of activities, then entering Vineland in step 2 would help control this measurement bias associated with parent reports. In step 3, we entered ESBQC. If ESBQC still predicted SBSOD after Vineland was being accounted for, then it would indicate that the relation between ESBQC and SBSOD was not simply because of similar measurement methods (i.e., parent report). See Table 4 for results. Most importantly, the R^2 change from step 2 to step 3 was significant. Adding ESBQC was able to explain an additional 12.7% of the variance in SBSOD. Collinearity statistics showed that none of the

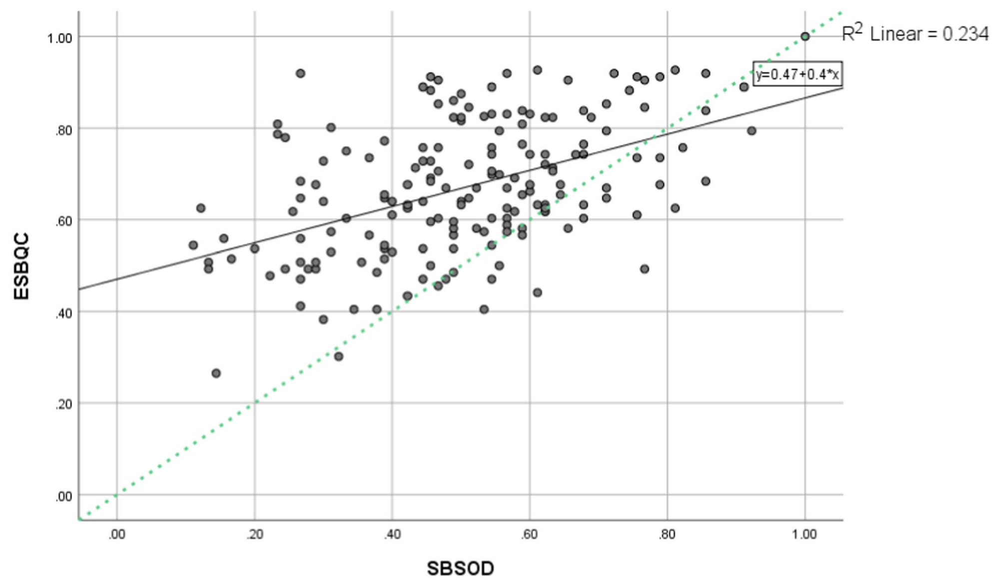

FIGURE 2
The relationship between SBSOD rescaled and ESQBC rescaled. The black solid line shows the regression line, whereas the green dotted line shows y=x.

variables had VIFs of over 10, hence there was minimal concern for collinearity.

We examined the relationship between SBSOD and ESBQC more closely. SBSOD was on a 7-Likert Scale (Hegarty et al., 2002) and ESBQC was on a 5-point Likert Scale (Lawton et al., 2015). To make the two scales comparable, we used the following formulas to transform the data:

SBSOD_rescaled = (SBSOD-1)/(5–1)

ESBQC_rescaled = (ESBQC-1)/(7–1)

This way, both questionnaires were on the same scale, ranging from 0 to 1, where 0.5 indicates a balance point (e.g., neither agree nor disagree). Then we plotted the two rescaled scores. See Figure 2 below. It is apparent that the relationship was positive such that increases in SBSOD were associated with increases in ESBQC. Furthermore, if the two sets of scores were perfectly aligned, they should form a perfectly diagonal line of $y = x$ (or $y = 0 + 1 * x$). As shown in the figure, most scores were above the diagonal line. In other words, most children found everyday spatial behaviors on the ESBQC easier than those on SBSOD.

Finally, we examined whether ESBQC could also predict child outcomes. The zero-order correlation between ESBQC and the child measure of Raven's 2 was significant, $r = 0.390$, $p < 0.001$. However, the partial correlation between the two after partialling out the effects of age was no longer significant, $r_p = 0.046$, $p = 0.559$. This also applied to SBSOD: while the zero-order correlation between SBSOD and Raven's 2 was significant, $r = 0.156$, $p = 0.042$, the partial correlation between the two after considering age was no longer significant, $r_p = 0.092$, $p = 0.248$.

Discussion

To better understand everyday activities relevant to informal STEM learning, we developed an everyday spatial behaviors questionnaire for children (ESBQC) based on prior research on adults (Eliot and Czarnolewski, 2007; Lawton et al., 2015). A total of 174 parents completed the ESBQC about their children. In addition, they completed the SBSOD and Vineland-3. Their children, aged 4–9 years old, completed the Raven's 2, a normed measure of general cognitive ability. Exploratory factor analyses showed 8 components, accounting for over 60% of the variance. Individual differences analyses showed that increasing age was associated with higher scores in ESBQC, yet there were no sex differences in ESBQC. Correlation analyses showed that ESBQC was significantly correlated with children's adaptive living skills, sense of direction, and cognitive ability. Regression analyses showed that ESBQC predicted SBSOD even after considering the effects of age and measurement bias associated with parent reports. However, ESBQC did not predict children's Raven's 2 after considering age.

Evaluating ESBQC

Our study showed the factor structures of ESBQC, its high internal reliability, and high converging validity. Our factor analysis generated 8 components, unlike the 12 subscales in the original studies of ESBQ for adults (Eliot and Czarnolewski, 2007; Lawton et al., 2015). One difference between our study and earlier studies is that ESBQC had much fewer items (46 total) relative to the original ESBQ adult version (i.e., 116 and 132). Moreover, while ESBQC focused on parents of children between 4 and 9 years old, the original ESBQ adult version studied college students. It is also important to note the multifaceted nature of everyday spatial behaviors. One spatial behavior may involve more than one type of spatial ability. For instance, when trying to find a missing puzzle piece, one would first decide and locate where the missing piece should go, recognize the unique spatial features of surrounding pieces, store this information in visual–spatial short-memory, visually search all the loose pieces, mentally or manually rotate a certain piece to see if it fits, and repeats this process until finding one that fits. During this process, spatial perception, spatial memory, and mental rotation would all have been involved. Therefore, the factor structures of everyday spatial behaviors may be more intertwined and complicated than those from laboratory spatial tasks. Reliability analysis showed acceptable to high reliabilities for 7 out of the 8 factors. We recommend using the 34 items, excluding component 8 with low reliability and all the items that did not load on any factors. The reliability of the 34-item ESBQC as a whole was very high: alpha = 0.95.

Our study also showed reasonable converging validity with SBSOD, which itself has been validated with experimental tasks (Hegarty et al., 2002). It is also interesting to consider the differences between the two measures. Scatterplots showed that everyday spatial behaviors on ESBQC were perceived to be less difficult for children relative to navigation-specific behaviors on SBSOD. Spatial navigation as assessed by SBSOD might represent the most difficult form of spatial cognition in our daily lives because navigation requires numerous cognitive abilities such as planning, reasoning, and decision-making (e.g., Brunyé et al., 2018; Dalton et al., 2019). Due to safety concerns, children also have fewer opportunities and experiences for independent spatial navigation compared with other types of spatial behaviors (e.g., make a bed) as investigated by ESBQC.

Although ESBQC correlated with Raven's 2 at the zero-order level, the partial correlation between the two after considering age was no longer significant. There are several reasons for the lack of significant relations after partial correlations. First, parent reports might not be reliable measures of child performance in laboratory settings. Parents may know how their children behave in daily life. However, this may not translate to a laboratory task that children have never experienced before. Second, Raven's 2 is a general measure of cognitive ability. Other cognitive measures that directly tap into spatial abilities, such as spatial perception tasks, sports-related movement tasks, and navigation tasks, may have a stronger relationship with ESBQC. However, we think that even though neither SBSOD nor ESBQC correlated with Raven's 2 after partialling out age, it does not necessarily diminish the utility of ESBQC. ESBQC is simply not measuring the same psychological construct that Raven's 2 is measuring. In fact, many daily behaviors, habits, and activities are better off being measured by questionnaires with higher ecological validity than cognitive tasks with high internal validity but much limited ecological validity. Future research should continue to explore the predictive validity of ESBQC.

Everyday spatial behaviors and informal STEM learning

We hope that ESBQC may help show parents and other stakeholders the wide array of everyday spatial behaviors that children are engaging in or could engage regularly. Often, in the eyes of a layperson, there is a disconnect between laboratory studies of spatial abilities and people's everyday experiences. Previous research has found that many parents may not recognize daily opportunities to engage their children in informal STEM learning (Gomes and Fleer, 2019; Zucker et al., 2021). For instance, mental rotation is widely understood by spatial cognition researchers but seems jargony, or at least unrelatable, to people outside the academe. Some common mental rotation examples in adult life could involve installing ink toners or assembling furniture. However, there is very little chance that 4-9-year-old children would engage in these behaviors. Our ESBQC included specific real-life examples that children may engage such as "Deciding whether a cutout shape will fit into a hold" and "Rotating an object that they are carrying (e.g., a toy) so that it can fit through a smaller door." ESBQC may be used in broader contexts outside of research. For instance, teachers and other educators can use examples from ESBQC to show parents ample daily opportunities to encourage children's spatial behaviors at home. ESBQC may also be used to identify different students' strengths and weaknesses, which would then help advise ways for more individualistic educational plans for STEM learning.

Identifying spatial behaviors in everyday settings in the first place may lead to training and teaching moments to promote spatial abilities and activities (Ramani et al., 2015; Pagano et al., 2019). This is particularly relevant to early childhood when children are not equipped to grapple with more complex spatial thinking and reasoning concepts in formal curricula. For instance, when playing with Legos or puzzles, parents may help children recognize 2D and 3D shapes and engage in spatial rotation, transformation, and imagery. When navigating in an unfamiliar environment, parents may help children notice the geometric structures of buildings and study the layout of the streets. The interests, engagement, and motivation developed early in childhood may also help develop the formation of STEM identity and learning and readiness later on (Maltese et al., 2014; Dou et al., 2019). For instance, the everyday spatial behavior of exploring and navigating in an unfamiliar spatial environment may encourage the development of wayfinding skills and interests relevant to STEM careers such as airplane pilots and architects. It may also promote understanding basic principles of urban design and geography. Overall, our results indicate the availability of ample opportunities to engage in informal STEM learning (Katz, 2011; Leyva et al., 2021) through everyday spatial behaviors, the potential of which might have yet to be fully explored by parents, educators, and other stakeholders.

Individual differences in everyday spatial behaviors

We found an age effect such that an increase in age was associated with better everyday spatial behaviors. The correlation coefficient between age and ESBQC was numerically the largest compared with correlation coefficients that ESBQC had with other variables. The age effect was expected and consistent with previous laboratory studies of spatial cognition in children (e.g., Merrill et al., 2016; Nazareth et al., 2018). There might be a bi-directional relation between spatial competency and spatial behaviors/activities frequency. Children's increasing competency in everyday spatial behaviors may encourage them to engage in more spatial behaviors in more contexts, which in turn further facilitates the improvement of their competency in everyday spatial behaviors. Social–emotional factors such as confidence may also play a role such that increasing competency in everyday spatial behaviors makes children more confident in their abilities, and this increased confidence leads to more activities and better competency. For instance, a young child who is good at Legos may continue to play more Legos as they grow older and become more confident in their spatial construction skills, leading to an even higher competency in Legos playing. These increased experiences, confidence, and competency in everyday spatial behaviors may facilitate the development of spatial cognition (Vasilyeva and

Lourenco, 2012; Jirout and Newcombe, 2015; Schug et al., 2022) and STEM success (Uttal and Cohen, 2012; Stieff and Uttal, 2015).

Despite previous research finding sex differences in everyday spatial behaviors in adults (e.g., Newcombe et al., 1983; Lawton et al., 2015), we did not find a sex difference in children aged 4–9 years old. A meta-analysis has found that effect sizes of sex differences in spatial wayfinding were typically smaller for children younger than 13 years old than for adults (Nazareth et al., 2019). Admittedly, boys often demonstrate strength compared with girls in certain laboratory tasks measuring wayfinding and mental rotation (Hoyek et al., 2011; Jansen et al., 2013; Merrill et al., 2016). However, in real-life situations, girls may have a repertoire of strategies available to compensate for a possible shortcoming in spatial abilities, if the shortcoming does exist. For instance, putting together puzzle pieces can benefit from attention to detail and visual processing (Powers et al., 2013) in addition to the assumed underlying spatial abilities such as spatial perception and mental rotation skills. Furthermore, in real-life situations, experience and opportunities to engage in spatial behaviors may play a bigger role than the assumed cognitive abilities. For instance, although a new student may need help finding their classroom on the first day of a new school, they typically have no trouble after one semester.

We also found that modality had a small correlation with ESBQC, such that in-person parents rated their children more favorably than online parents. This result was unexpected. It is possible that in-person parents have a stronger motivation for social desirability in front of the experimenters than online parents (however, see Dodou and de Winter, 2014). There are also alternative possibilities, such as the impact of Covid on parental stress (Adams et al., 2021). Future research can explore the online vs. in-person difference in more detail.

Conclusion

Spatial thinking is critical to STEM success because many STEM problems involve spatial thinking and reasoning (Uttal and Cohen, 2012; Stieff and Uttal, 2015). Spatial cognition is also highly malleable (Uttal et al., 2013; Stieff and Uttal, 2015; Reilly et al., 2017) and can be improved through experience, practice, and instructions. However, it is not typically taught in the K-12 curriculum (Kell and Lubinski, 2013). By examining everyday spatial behaviors in children aged 4–9 years old, our study showed that there are many daily opportunities to engage, motivate and promote informal STEM-related activities during early childhood. We hope our study will encourage more attention, interest, and awareness of informal STEM-related activities in future research.

Data availability statement

Data are available on request to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by Institutional Review Board, Montclair State University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

YY contributed to the conception, design, and analysis of the study and wrote the first draft of the manuscript. SC organized the database, analyzed the data, and contributed to sections of the manuscript. DL, AH, and LG coordinated the study, collected data, and organized the database. LG contributed to the design of the study. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Mothers' and fathers' engagement in math activities with their toddler sons and daughters: The moderating role of parental math beliefs

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Parents' beliefs about the importance of math predicts their math engagement with their children. However, most work focuses on mothers' math engagement with preschool- and school-aged children, leaving gaps in knowledge about fathers and the experiences of toddlers. We examined differences in mothers' and fathers' (N = 94) engagement in math- and non-math activities with their two-year-old girls and boys. Parents reported their beliefs about the importance of math and literacy for young children and their frequency of home learning activities. Parents of sons did not differ in their engagement in math activities from parents of daughters. Mothers reported engaging more frequently in math activities with their toddlers than fathers did, but the difference reduced when parents endorsed stronger beliefs about the importance of math for children. Even at very early ages, children experience vastly different opportunities to learn math in the home, with math-related experiences being shaped by both parent gender and parents' beliefs.

KEYWORDS

home numeracy, math activities, gender roles, toddlers, math beliefs, fathers

Introduction

Expectancy-Value Theory emphasizes connections among individuals' values, expectations, and behaviors (Wigfield and Eccles, 2000). For example, as parents' value for an activity increases, or the more they expect their child to enjoy, benefit, or succeed in a domain, the more frequently they should engage in that activity with their child. However, values and expectations do not emerge in a vacuum. Many factors affect parents' values and expectations, including their beliefs around gender such as what skills girls or boys should learn and what activities mothers and fathers should engage in with their children. In this study, we examine parent–child math-related activities under the framework of Expectancy-Value Theory and consider how children's and parents' gender shape toddlers' home engagement in math.

Mathematics provides an ideal domain for examining the role of parents' expectations and attitudes, particularly in light of gender disparities in engagement. Gendered beliefs about math include stereotypes that math is a male-dominated domain (see Frost et al., 1994; Nosek et al., 2002) and that math requires innate brilliance (much more frequently attributed to males; see Chestnut et al., 2018). Adults' math-gender stereotypes predict their expectations and values for boys' and girls' math achievement (see Eccles et al., 1990; Gunderson et al., 2012). Furthermore, parents' gendered math attitudes and beliefs are associated with their children's endorsement of gendered math attitudes and beliefs (e.g., Tenenbaum and Leaper, 2002; Hildebrand et al., 2022). Critically, by early-to mid-elementary school, children's own math attitudes and beliefs are associated with their math achievement (see Levine and Pantoja, 2021).

Why study math engagement in toddlers?

Math is a fundamental skill related to career choice, employment and income, and health and financial decision-making (Trusty et al., 2000; Currie and Thomas, 2001; Reyna and Brainerd, 2007; Agarwal and Mazumder, 2013). Individual differences in math performance emerge in early childhood (Starkey and Klein, 1992; Jordan et al., 2006) and predict children's later math achievement and educational attainment throughout the school years and into adulthood (Duncan et al., 2007; Jordan et al., 2009; Siegler et al., 2012; Nguyen et al., 2016). Given the importance of math skills for daily life, much attention has been paid to identifying factors related to individual differences in early math achievement. Many contributing factors, including genetics (Hart et al., 2009) and social and environmental influences contribute to variability in early math performance (Jordan and Levine, 2009; Silver and Libertus, 2022).

Children's home environment is a key influence that has received considerable attention, in particular, the extent to which parents engage in math-related activities with their children (Mutaf-Yildiz et al., 2020; Daucourt et al., 2021). Frequent home math activities, such as measuring ingredients while cooking or playing board games with dice or spinners, support children's math performance (Blevins-Knabe and Musun-Miller, 1996; LeFevre et al., 2009; Kleemans et al., 2012; Niklas and Schneider, 2013; Ramani et al., 2015; Huntsinger et al., 2016; Mutaf Yildiz et al., 2018). However, relations are not always replicated (see Elliott and Bachman, 2018; Hornburg et al., 2021), suggesting that associations are complex and may depend on factors such as activity type (e.g., differences between formal, direct activities like doing number flashcards and informal, indirect activities like talking about money while shopping; Skwarchuk, 2009; DeFlorio and Beliakoff, 2014; Missall et al., 2014; Girard et al., 2021; Leyva et al., 2021), the quality of parent–child interactions while engaging in math activities (Elliott and Bachman, 2018), and children's age (Thompson et al., 2017). Nonetheless, meta-analyses and systematic reviews of the literature suggest that home math engagement is helpful for children's math performance, especially in early childhood (see Dunst et al., 2017; Mutaf-Yildiz et al., 2020; Daucourt et al., 2021). Investigating the factors that predict parental engagement in math activities with young children may therefore advance an understanding of how to support children's early math development.

Previous work has focused primarily on factors related to variability in home math engagement in preschool-and school-aged children, with minimal attention to factors that contribute to home math engagement with infants and toddlers. However, variations in foundational number skills already emerge in infancy (e.g., Libertus and Brannon, 2010; Starr et al., 2013). Given the benefits of math engagement for the development of math skills in preschoolers and older children (e.g., Daucourt et al., 2021), further work is needed to understand how and why parents engage in math activities with younger children. Here, we describe parents' math activities with their toddlers. We focus on child and parent characteristics found to be associated with parents' engagement in general learning activities with toddlers and factors found to be associated with parents' engagement in math activities with preschool-and school-aged children in prior studies.

Parents' home math activities with sons and daughters

We examined characteristics associated with differences in parents' general engagement with toddlers to identify if similar relations apply to math engagement. One such factor is children's gender, which has been studied extensively in other domains. The frequency with which parents engage in different types of home activities often differs for sons and daughters (see Morawska, 2020 for review). As early as infancy, parents hold different beliefs about the appropriate activities for boys and girls and tend to engage their sons in more physical play activities and daughters in more literacy activities (Leavell et al., 2011; Kroll et al., 2016; Dinkel and Snyder, 2020).

However, previous studies present conflicting results on parents' math-specific engagement with sons and daughters. Some find that parents are more inclined to engage in math activities with their sons than with their daughters (Chang et al., 2011; Hart et al., 2016), whereas other studies indicate the reverse (Blevins-Knabe and Musun-Miller, 1996; Jacobs and Bleeker, 2004; del Río et al., 2017), or find no association between child gender and math engagement at home (Jordan et al., 2006; De Keyser et al., 2020; Zippert and Rittle-Johnson, 2020). Given the limited number of studies on the topic, and inconsistent findings, further inquiry into associations between child gender and math engagement at home is warranted.

Mothers' and fathers' math engagement with children

Existing research on parents' math engagement focuses on mothers (Blevins-Knabe and Musun-Miller, 1996; Jacobs and Bleeker, 2004; Byrnes and Wasik, 2009; del Río et al., 2017; De Keyser et al., 2020; Thippana et al., 2020; Zippert and Rittle-Johnson, 2020), pointing to the need to understand similarities and differences in how mothers and fathers engage their daughters and sons in math.

Mothers and fathers exhibit both similarities and differences in their style, quality, and frequency of engagement with young children in various activities, such as caregiving, reading, language input, and general cognitive stimulation activities, and father involvement uniquely relates to behaviors and developing skills in children after controlling for mothers' involvement (Laflamme et al., 2002; Duursma et al., 2008; Baker, 2013; Duursma, 2014; Varghese and Wachen, 2015; Rolle et al., 2019; Cabrera et al., 2020). Mothers and fathers differ in how often they engage in literacy activities with their toddlers and how they read to them (e.g., Malin et al., 2014; Cabrera et al., 2020). Specifically, although mothers tend to engage more frequently in literacy activities (e.g., Burgess, 2010; Malin et al., 2014), fathers tend to use more complex and challenging language with their children (Ely et al., 1995; Rowe et al., 2004; Malin et al., 2014). Although research exists on differences in mothers' and fathers' talk and involvement with children about broader STEM topics (e.g., Crowley et al., 2001; Eccles, 2015), comparison of mothers' and fathers' math-specific engagement with children has received less attention.

Prior work comparing fathers' and mothers' involvement in math activities is considerably scarce and has focused exclusively on preschool-and school-aged children (e.g., Ramani et al., 2015; Elliott et al., 2017; Silver et al., 2020; Thippana et al., 2020). The handful of studies that have examined fathers' home math-related engagement (focused on preschool-and school-aged children from different socioeconomic and cultural backgrounds) yield inconsistent results (Jacobs and Bleeker, 2004; Foster et al., 2016; Hart et al., 2016; del Río et al., 2017, 2019). Findings from two studies indicate that mothers may be more involved than fathers in math activities with their preschool-and kindergarten-aged children at home (Foster et al., 2016; del Río et al., 2019). However, others find no differences in mothers' and fathers' math engagement with kindergarten and school-aged children (Jacobs and Bleeker, 2004; del Río et al., 2017). Conflicting findings may be due to differences across studies in the types of math activities measured: In one study, mothers reported engaging in more numeracy activities than did fathers, but fathers reported engaging more frequently in overall home math activities (i.e., an overall composite of numeracy activities and spatial activities, such as drawing maps and measuring length and width) relative to mothers (Hart et al., 2016).

Inconsistent results across studies may be explained by differences in children's age, other sample characteristics such as socioeconomic background, or the type of math activities measured. Even less is known about children's engagement in math activities with their mothers and fathers during toddlerhood, the focus of this investigation.

Parents' math beliefs and math engagement

Mothers and fathers have been found to differ in math-related beliefs regarding sons and daughters (see Waters et al., 2022) in ways that may affect their math engagement. In particular, multiple types of math beliefs are found to influence parents' engagement with preschool-and school-aged children, including parents' perceptions of their role in their child's math learning (Stipek et al., 1992; DeFlorio and Beliakoff, 2014; Sonnenschein et al., 2016), and beliefs about the importance of various academic subjects, including math (Cannon and Ginsburg, 2008; LeFevre et al., 2009; Puccioni, 2014).

Parents who hold strong beliefs about the importance of math for children (i.e., that math is an important skill for young children to learn) report engaging in frequent math-related activities with their preschool-and school-aged children (Musun-Miller and Blevins-Knabe, 1998; Cannon and Ginsburg, 2008; LeFevre et al., 2009; Sonnenschein et al., 2012; Muenks et al., 2015; Zippert and Ramani, 2017; Silver et al., 2021). Notably, these beliefs about the importance of math buffer against the negative consequences of math anxiety on parents' engagement in math with their preschool-aged children (Silver et al., 2021).

However, most previous work focused on the math-related beliefs of parents of preschool-and school-aged children. Studies that targeted beliefs of parents with infants and toddlers largely examined parents' beliefs about parenting, such as their role in co-parenting, the importance of play, and their goals for children (e.g., Coleman and Karraker, 2003; Rowe and Casillas, 2011; Favez et al., 2015; Manz and Bracaliello, 2016), and uniformly find positive associations between beliefs and engagement. It remains unknown whether parents' math-specific beliefs, and in particular their beliefs about the importance of math, predict their math engagement with toddlers.

The current study

We sought to identify whether child and parent gender and parents' beliefs about the importance of math relate to parental engagement in math activities with toddlers. We first explore whether children's and/or parents' gender relate to differences in home math activities. Based on inconsistent prior findings, we were uncertain about the role of children's and parents' gender in parents' math activities. Second, we investigate associations between parents' beliefs about the importance of math for young children and their home math activities. We expected these math beliefs to positively relate to parents' engagement in math activities with their children, based on prior work with parents of older children (Musun-Miller and Blevins-Knabe, 1998; Cannon and Ginsburg, 2008; LeFevre et al., 2009; Sonnenschein et al., 2012; Muenks et al., 2015; Zippert and Ramani, 2017; Silver et al., 2021), and in line with the idea that strong beliefs about the importance of math increase the value parents place on math engagement with their children (Wigfield and Eccles, 2000). Next, we examine whether parents' beliefs about the importance of math moderate the effects of children's and parents' gender on parents' math activities. We expected associations between children's and parents' gender and parents' frequency of engaging in math activities to be moderated by parents' beliefs about math, such that stronger beliefs about the importance of math might buffer (i.e., reduce) gender differences in math activities. Prior work shows that parents' positive beliefs about children's abilities and the importance of school can buffer against children's low school attitudes, expectations, and performance (Wigfield and Gladstone, 2019), and specifically that parents' beliefs about the importance of math buffer against the negative influence of parental math anxiety (Silver et al., 2021).

Finally, we examine the robustness and domain-specificity of these effects to determine whether associations are specific to math or apply to parental engagement broadly. To test specificity of associations, we controlled for other potentially confounding family characteristics, including children's age, parents' education, parents' language, parents' beliefs about the importance of domains other than math, and parents' engagement in non-math activities. Although children were all 2 years of age, we controlled for children's age given prior findings that parents may change their engagement in math activities as children develop (e.g., Thompson et al., 2017; Daucourt et al., 2021). We controlled for parents' education and language to ensure that any differences in math activities were not due to socioeconomic or cultural assimilation differences between families (see Vigdor, 2009; Eason et al., 2022). We controlled for parents' beliefs about the importance of literacy and engagement in non-math activities to test whether associations were specific to parents' beliefs about the importance of math and math activities, rather than beliefs about the importance of academic skills generally or engagement in learning activities broadly. Finally, to further probe the specificity of these associations, we ran follow-up analyses on parents' beliefs about the importance of literacy and non-math activities.

Method

Participants

Data were drawn from a multi-site study on how mothers and fathers from ethnically diverse two-parent households support their two-year-old children's acquisition of academic skills. Participants were 94 parents of toddlers (52 mothers, 42 fathers; 40 families had both the child's mother and father participate) from the New York City, New York (26 parents), Pittsburgh, Pennsylvania (28 parents), and College Park, Maryland (40 parents) metropolitan areas of the United States. An additional four parents participated in the study but did not complete all measures and were not included in analyses. Parents were Hispanic/Latino (65%) and White, non-Hispanic/Latino (35%). Half indicated a preference to participate in English ($n = 47$) and half chose to participate in all tasks in Spanish ($n = 47$). Participants averaged 13.10 years of education (SD = 3.77 years; range from 4 years to 17 years).

Procedure

Participants were recruited *via* flyers, online postings, and in-person recruitment at local daycare centers in three metropolitan areas of the eastern United States. Due to the broader aims of the study, families were eligible to participate if both parents lived at home with the child, had obtained no more than a Bachelor's degree, spoke only English and/or Spanish, and were either White, non-Hispanic/Latino or Hispanic/Latino. At each site, mothers and fathers and their children participated in two home visits. Parents were told that the study focused on how parents play with their young children and support toddlers' development in the home, and they were not told that the focus of the study was on math. The data used for this project are drawn from a self-report questionnaire that all parents completed with researchers during the home visit, describing their frequency of engaging in learning activities with their child, their attitudes, beliefs, and anxiety about engaging in various academic activities, and demographic information about their family. Parents also completed math and spatial assessments, a non-symbolic number comparison task, and participated in semi-structured observations with their child. These measures were not the focus of this study, and so are not discussed further. Each parent received $50 for participation.

Measures

Parents' home learning activities

Each parent reported the frequency of home learning activities they engage in with their child. The full list of items can be found in the Supplemental Material. Parents were asked to indicate how often in the past month they had participated in listed activities (e.g., 11 math activities such as "Counting objects"; 9 non-math activities such as "Coloring, painting, writing" or "Identifying names of written alphabet letters") with their child on a scale from 1 ("Did not occur") to 5 ("Almost daily"), with additional options to indicate whether the listed activity was not appropriate for their child due to age or was not appropriate for their family because they did not own the items necessary to engage in the activity (which was scored as "NA"). Responses for the 11 math-related items were averaged to create a math activities score, and responses for the 9 non-math items were averaged to create a non-math activities score.

Parents' beliefs about the importance of math and literacy for young children

Each parent reported their beliefs about the importance of math and literacy for young children using the Benchmarks Survey from the Home Numeracy Questionnaire (LeFevre et al., 2009). The full list of items can be found in the Supplemental Material. They were asked, "In your opinion, how important is it for children to reach the following benchmarks prior to entering kindergarten?" on a scale from 1 ("Not at all important") to 5 ("Very important"). Items included parents' beliefs about the importance of five math skills (e.g., "Count to 100″) and four reading and writing skills (e.g., "Print alphabet letters"). Responses to the five math items were averaged to create a belief about the importance of math score, and responses to the four literacy items were averaged to create a belief about the importance of literacy score.

Children's and parents' gender

Child and parent gender were coded using effects coding (where female = 0.5, male = −0.5).

Family demographic information

Parents reported their child's birthdate, which was used to calculate the child's age in months on the date of testing. In addition, each parent reported how many years of school they had completed, and the language that they preferred to use for testing.

Data analysis and model fitting

Due to the clustering present in our data (where individual parents are nested within families, and families are nested within three sites of data collection), mixed effects models predicting the frequency of parents' engagement in math activities with their children were tested and compared using the *lme4* and *lmertest* packages in R (Bates et al., 2007; Kuznetsova et al., 2017). All tested models included random effects for family and site, and prior to analysis we standardized all variables to allow for ease of interpretation of results. In a series of hierarchical mixed effects models, we predicted parents' engagement in math activities.

In Model 1, we predicted parents' engagement in math activities from fixed effects of children's gender, parents' gender, and parents' beliefs about the importance of math. In Model 2, we used the same fixed effects as in Model 1, with the addition of an interaction between children's gender and parents' beliefs about the importance of math. In Model 3, we used the same fixed effects as in Model 1, with the addition of an interaction between parents' gender and parents' beliefs about the importance of math.

Follow-up models testing for robustness and domain-specificity

For any significant interactions found in Models 2 or 3, we ran follow-up analyses controlling for possible confounds (Step 4), testing robustness of the results (Step 5), and examining the domain-specificity of the interactions (Steps 6 and 7).

To control for possible confounds of family demographic characteristics, in Step 4 we added fixed effects of children's age, parents' education, and parents' language used. As a particularly stringent test of the robustness of our results, in Step 5 we added fixed effects of parents' non-math activity engagement and parents' beliefs about the importance of literacy.

Finally, in Steps 6 and 7 we explored the domain-specificity of associations (i.e., whether associations were characteristic of parents' activities with their toddlers broadly or specific to their math activities). Specifically, in Step 6, for significant interactions in Models 2 or 3, we first tested a model predicting parents' engagement in non-math activities from those same predictors and controlling for math activities. A significant interaction in predicting non-math activities would indicate that associations are not specific to math. In contrast, a non-significant interaction would suggest that the association is specific only to math activities.

In Step 7 we tested a second follow-up model predicting parents' engagement in math activities from the same predictors but using parents' beliefs about the importance of literacy in the interaction (instead of their beliefs about the importance of math). A significant interaction between parents' beliefs about the importance of literacy and children's or parents' gender would indicate a domain-general association (as parental beliefs about the importance of skills across domains moderate associations of gender with math engagement). However, a non-significant interaction would suggest that the association is specific to beliefs about the importance of math specifically.

Model fitting

This dataset included data at three different levels, such that Level 1 is the individual parent participant, Level 2 is the family from which each parent comes, and Level 3 is the site from which each family was recruited and tested. In all models, random effects included intercepts for each family and each data collection site to account for clustering within families and within geographic sites of data collection. The maximal models were initially tested but failed to converge. To maintain the maximal random effects structure, the correlation parameters were removed from the models. This led the models to converge but they remain overfitted as indicated by a "singular fit" warning. To further reduce model complexity, the random slopes for children's age, parents' years of education, parents' frequency of engaging in non-math activities, parents' beliefs about the importance of math and parents' beliefs about the importance of literacy (which had all been included for both family and site to account for potential differences in how the fixed effects may relate to math activities within families and sites) were removed. Model comparison indicated that models not containing random slopes better fit the data [with lower Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC)], and the statistical significance of all main effects and interactions remained consistent in models with the inclusion and exclusion of the random slopes. Therefore, for parsimony, the final models did not include the random slopes or correlations.

Results

Descriptive statistics of parents' math activities with their toddlers are presented in Table 1. Parents engaged in math activities with their toddlers on average about once a week (Mean = 3.09; Median = 3.18) with wide variability (ranging from never to almost daily). Over 54% of parents reported engaging in math activities more than once per week. Parents reported engaging more frequently in non-math activities (Mean = 3.52, corresponding to between once a week and a few times a week; Median = 3.67) than math activities, $t(93) = -6.56$, $p < 0.001$. Over 76% of parents reported engaging in non-math activities more than once per week, and more than 77% of parents reported more frequent non-math activities than math activities. Item-level descriptive statistics for the home learning activities measure can be found in Table 2.

Parents' beliefs about the importance of math for young children also varied widely, with parents reporting on average that they believed math was moderately to quite important (Mean = 3.68; Median = 3.80), with beliefs ranging from not at all important to very important. Over 34% of parents reported that math was quite important or very important. Parents' beliefs about the importance of literacy for young children (Mean = 4.16, corresponding to between quite important and very important; Median = 4.25) were significantly higher than their beliefs about the importance of math, $t(93) = -7.27$, $p < 0.001$. Over 54% of parents reported beliefs that literacy was quite important or very important, and over 85% of parents reported higher beliefs about the importance of literacy than about the importance of math.

We next asked whether parents' frequency of engaging in math activities differed with sons and daughters or for mothers and fathers, and whether parents' beliefs about the importance of math moderated these associations (results from Models 1–3 can be found in Table 3). In all models we included random effects of family and site, which together accounted for 18.1% of the variance in parents' engagement in math activities. Model 1 tested fixed effects of children's gender, parents' gender, and parents' beliefs about the importance of math on parents' math activities, and explained 7.4% of the variance in math activities. Parents of sons and parents of daughters did not differ in their reported math activities, but overall mothers engaged in significantly more frequent math activities than fathers did ($B = 0.40$, 95% CI [0.11, 0.70], $p = 0.011$). Contrary to hypotheses, we found no significant main effect of parents' beliefs about the importance of math on math activities.

We next tested whether parents' beliefs about the importance of math might moderate associations between children's or parents' gender and parents' math activity engagement. Model 2 tested whether parents' beliefs about the importance of math moderate the association between children's gender and parents' math activities but found no significant interaction. In Model 3 a significant interaction was found between parents' beliefs about the importance of math and parents' gender ($B = -0.31$, 95% CI [−0.63, 0.00]), such that the effect of parents' gender (where mothers engage in more frequent math activities than fathers) is reduced when parents hold strong beliefs about the importance of math for young children. Model 3 accounted for significantly more variance in math activities than Model 1 ($\Delta R^2 = 0.03$, 95% CI [0.02, 0.05], $p < 0.001$), and was a marginally significantly better fit of the data than Model 1, $\chi^2(1) = 3.27$, $p = 0.07$. Critically, the pattern of main effects from Model 1 remained similar

TABLE 1 Descriptive statistics for study variables.

Variable	Overall *M* (SD)	Overall Range	Mother *M* (SD)	Father *M* (SD)	Child Female *M* (SD)	Child Male *M* (SD)	Spanish *M* (SD)	English *M* (SD)
Math activities	3.09 (0.82)	1.00–4.57	3.25 (0.67)	2.88 (0.94)	3.01 (0.83)	3.16 (0.80)	3.03 (0.87)	3.14 (0.76)
Math beliefs	3.68 (0.88)	1.20–5.00	3.60 (0.89)	3.79 (0.87)	3.74 (0.83)	3.62 (0.93)	3.80 (0.92)	3.56 (0.83)
Literacy beliefs	4.16 (0.84)	1.00–5.00	4.15 (0.87)	4.18 (0.80)	4.19 (0.74)	4.14 (0.93)	4.21 (0.79)	4.11 (0.89)
Child age (months)	30.78 (3.58)	24.26–36.39	30.60 (3.64)	31.00 (3.53)	31.10 (3.94)	30.40 (3.19)	30.20 (3.50)	31.40 (3.58)
Parent education (years)	13.10 (3.77)	4.00–17.00	13.10 (3.69)	13.10 (3.90)	13.10 (4.02)	13.10 (3.55)	11.70 (4.01)	14.50 (2.96)
Non-math activities	3.52 (0.75)	1.00–4.75	3.70 (0.66)	3.29 (0.80)	3.55 (0.75)	3.48 (0.76)	3.32 (0.83)	3.71 (0.61)
Variable	**Overall *N***		**Mother *N***	**Father *N***	**Child Female *N***	**Child Male *N***	**Spanish *N***	**English *N***
Child gender Female	46		26	20	-	-	24	22
Child gender Male	48		26	22	-	-	23	25
Language Spanish	47		26	21	24	23	-	-
Language English	47		26	21	22	25	-	-

Overall *N* = 94 (Mother *N* = 52, Father *N* = 42; Child Gender Female *N* = 46, Child Gender Male *N* = 48; Language Used Spanish *N* = 47, Language Used English *N* = 47). Activities frequency could range from 1 ("did not occur") to 5 ("almost daily"), and beliefs about the importance of skills could range from 1 ("not important") to 5 ("very important").

in Model 3, with a significant effect of parents' gender ($B = 0.41$, 95% CI [0.13, 0.70], $p = 0.007$) and no main effect of children's gender and parents' beliefs about the importance of math.

Given the significant interaction between parents' beliefs about the importance of math and parents' gender in Model 3, we next tested the robustness of results in a series of follow-up analyses. In Model 4, we used the same predictors as in Model 3 and included fixed effects of children's age, parents' education, and parents' language as controls. Parents' gender continued to predict math activities ($B = 0.40$, 95% CI [0.11, 0.69], $p = 0.010$), and the interaction between beliefs about the importance of math and parents' gender also remained significant ($B = -0.35$, 95% CI [−0.68, −0.02], $p = 0.039$) even with the addition of these control variables. In Model 5 we added fixed effects of parents' non-math activities and parents' beliefs about the importance of literacy to Model 4 for a final stringent robustness check. Model 5 explained 49.4% of the variance in parents' math activities and was a significantly better fit than any of the previously tested models. Although the main effect of parents' gender was no longer significant in Model 5, even with the addition of these stringent control variables the interaction between parents' beliefs about the importance of math and parents' gender remained significant ($B = -0.32$, 95% CI [−0.56, −0.07], $p = 0.014$; see Figure 1). Results from Models 4 and 5 can be found in Table 4.

To explore domain-specificity of the significant interaction between parents' beliefs about the importance of math and parents' gender, we tested follow-up Models 6 and 7. Model 6 predicted parents' engagement in non-math activities from the same set of predictors as Model 5. The interaction between parents' beliefs about the importance of math and parents' gender did not predict parents' non-math activities ($B = 0.17$, 95% CI [−0.6, 0.40], $p = 0.154$). Finally, Model 7 predicted parents' engagement in math activities from the same set of predictors as Model 5, but with an interaction between parents' beliefs about the importance of literacy (rather than beliefs about the importance of math) and parents' gender. The interaction between parents' beliefs about the importance of literacy and parents' gender was not significant in predicting parents' math activities ($B = -0.22$, 95% CI [−0.48, 0.03], $p = 0.087$). The results of Models 6 and 7 (which can be found in Table 5) suggest that the interaction between parents' beliefs about the importance of math for young children and parents' gender are domain-specific to math activities and beliefs about the importance of math.

Discussion

Parental engagement in math activities at home has been found to predict children's math skills, but this work has primarily focused on preschool-and school-aged children (e.g., LeFevre et al., 2009; Mutaf-Yildiz et al., 2020; Daucourt et al., 2021). Here, we find that parents differ widely in their engagement in math activities with toddlers, and that parents' beliefs about the importance of math and parents' gender play a role in parents' engagement in math activities with toddlers. Furthermore, we find that the effects of parents' beliefs about the importance of math (in interaction with parent gender) are specific to the domain of math.

We found that the main effect of children's gender was not significant. Instead, and in line with some other past work studying preschool-and school-aged children (Jordan et al., 2006; De Keyser et al., 2020; Zippert and Rittle-Johnson, 2020), parents did not differ in their math activities with 2-year-old sons and daughters. Similarly,

TABLE 2 Item-level descriptive statistics for home learning activities.

Home learning activity	*M* (SD)	Number of "My child is still too young for that" Responses	Number of "Do not have" Responses
Counting objects	4.13 (1.15)	0	0
Sorting things by size, color or shape	3.33 (1.25)	0	0
Counting down	2.45 (1.45)	6	0
Identifying names of written numbers	3.06 (1.54)	4	0
Picking up sticks, objects, etc.	4.33 (1.18)	1	0
Buttoning buttons	2.37 (1.41)	11	0
Movement songs (i.e., Itsy Bitsy Spider)	4.16 (1.26)	4	0
Coloring, painting, writing	3.97 (1.21)	0	0
Identifying names of written alphabet letters	3.48 (1.41)	6	0
Identifying sounds of alphabet letters	3.09 (1.45)	7	0
Making music	3.72 (1.44)	0	0
Playing with number fridge magnets	2.70 (1.59)	0	31
Putting pegs in a board or shapes into holes	3.26 (1.38)	0	20
Playing with puzzles	3.14 (1.32)	0	11
Building with blocks or construction sets (Duplo, Megablocks, etc.)	3.87 (1.20)	0	12
Playing with "Playdoh," dough, or clay	3.05 (1.47)	0	15
Using number activity books (like connect-the-dots)	2.53 (1.43)	0	13
Playing board games with numbers	2.03 (1.26)	0	29
Reading books that teach simple shapes like squares, circles, and triangles	3.12 (1.39)	0	5
Recite nursery rhymes (such a "Mother Goose") or read other rhyming books	3.27 (1.49)	0	12

Frequency of activities ranged from 1 ("Did not occur") to 5 ("Almost daily"). Parents were given options to indicate if "My child is still too young for that" or if they "Do not have" the physical materials to participate.

TABLE 3 Mixed effects models predicting parents' engagement in math activities.

	Model 1		Model 2		Model 3	
Fixed effect	*B*	95% CI	*B*	95% CI	*B*	95% CI
Intercept	3.06**	[2.81, 3.31]	3.06**	[2.82, 3.31]	3.04**	[2.75, 3.34]
Child gender	−0.12	[−0.46, 0.22]	−0.12	[−0.47, 0.23]	−0.06	[−0.41, 0.29]
Parent gender	0.40*	[0.11, 0.70]	0.40*	[0.11, 0.71]	0.41**	[0.13, 0.70]
Math beliefs	0.11	[−0.06, 0.27]	0.10	[−0.06, 0.27]	0.12	[−0.05, 0.28]
Child gender X Math beliefs	–	–	−0.04	[−0.36, 029]	–	–
Parent gender X Math beliefs	–	–	–	–	−0.32*	[−0.63, 0.00]
Random effect	SD		SD		SD	
Family intercept	0. 32		0.32		0.37	
Site intercept	0.16		0.16		0.21	
Residual	0.72		0.72		0.68	

*$p < 0.05$; **$p < 0.01$.

although parents' gender significantly predicted their math activities in some models, when controlling for parents' beliefs about the importance of literacy skills and their engagement in non-math activities this main effect disappeared. Together with inconsistent findings in the literature (e.g., Blevins-Knabe and Musun-Miller, 1996; Jacobs and Bleeker, 2004; Chang et al., 2011; Foster et al., 2016; del Río et al., 2017, 2019; Thippana et al., 2020), our findings suggest the need for further inquiry into the specific contexts in which children's and parents' gender relate to math engagement.

Existing studies vary widely on the types of math engagement measured (e.g., math activities versus math talk), the ages of children involved (e.g., toddlers versus preschool-aged versus school-aged children), the methods of data collection (e.g., parent-report measures versus direct observations), the countries of origin for participants (e.g., Chile versus Belgium versus the United States), the demographics of the families involved (e.g., predominantly middle-to upper-income versus lower-income), the gender of parents involved in the study (e.g., predominantly mothers versus mothers and fathers), and the historical cohort of parents in the samples (e.g., 1970s versus 2010s). Therefore, conflicting results across studies are unsurprising, and point to the need to consider variables that may moderate associations between children's and parents' gender and parent–child math engagement.

Indeed, we find that parents' beliefs about the importance of math moderated the effects of parent gender on math activities. Mothers and fathers differed in their engagement in math activities, but only in the presence of low parental beliefs about the importance of math for young children, such that mothers engaged in more frequent math activities than fathers did. When parents held strong beliefs about the importance of math, these gender differences reduced. Unmeasured parent beliefs may explain some of the inconsistent gender findings in the literature: If differences in math engagement by children's and parents' gender emerge only in some contexts (i.e., in the presence of particular parental math beliefs), samples in previous studies may have differed in their math beliefs.

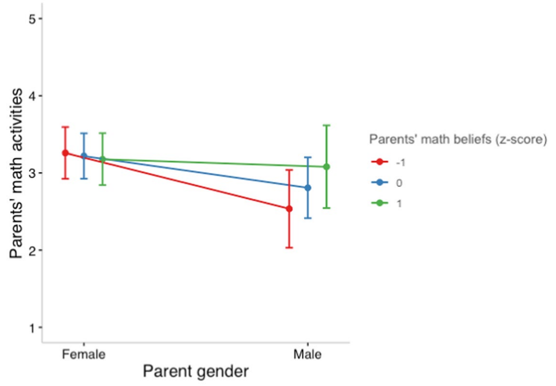

FIGURE 1
Interaction between parents' gender and parents' beliefs about the importance of math for young children predicting parents' math activities. The frequency of parents' home math activities ranged from 1 ("Did not occur") to 5 ("Almost daily").

Parents' beliefs about the importance of math for young children

Previous work with older children found that parents' beliefs about the importance of math for their children related to their frequency of engagement in math activities (e.g., Musun-Miller and Blevins-Knabe, 1998; Cannon and Ginsburg, 2008; LeFevre et al., 2009; Sonnenschein et al., 2012; Muenks et al., 2015; Zippert and Ramani, 2017; Silver et al., 2021). Contrary to these findings, we did not find such an association for parents of toddlers. Perhaps parents of toddlers, whose children are still years away from beginning kindergarten and formal education, do not yet hold strong beliefs about the importance of math; as children begin formal schooling, parents may increase their beliefs about math's importance. Future work on parents' beliefs about the importance of math for young children of different ages may prove useful to test how child age may shape parent beliefs.

We further examined whether associations between parents' beliefs about the importance of math and their engagement in math activities might differ based on children's or parents' gender. Along with a null effect of children's gender, parents' beliefs about the importance of math for young children did not moderate the effect of children's gender on math engagement. Thus, parents of sons and parents of daughters were similar in their frequency of math activities, regardless of their beliefs about the importance of math. In contrast,

TABLE 4 Follow-up mixed effects models predicting parents' engagement in math activities with additional control variables.

	Model 4		Model 5	
Fixed effect	***B***	**95% CI**	***B***	**95% CI**
Intercept	3.04*	[2.82, 3.26]	3.06*	[2.88, 3.24]
Child gender	−0.07	[−0.42, 0.28]	−0.13	[−0.39, 0.13]
Parent gender	0.40*	[0.11, 0.69]	0.08	[−0.15, 0.32]
Math beliefs	0.13	[−0.03, 0.30]	0.13	[−0.06, 0.31]
Parent gender X math beliefs	−0.35*	[−0.68, −0.02]	−0.32*	[−0.56, −0.07]
Child age	−0.12	[−0.29, 0.06]	−0.12	[−0.25, 0.02]
Parent education	0.09	[−0.09, 0.27]	−0.01	[−0.14, 0.13]
Language used	0.13	[−0.26, 0.52]	−0.11	[−0.42, 0.68]
Non-math activities	–	–	0.55***	[0.42, 0.68]
Literacy beliefs	–	–	−0.12	[−0.29, 0.06]
Random effect	**SD**		**SD**	
Family intercept	0.35		0.22	
Site intercept	0.12		0.11	
Residual	0.70		0.54	

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

TABLE 5 Follow-up mixed effects models testing domain-specificity of results predicting parents' engagement in non-math activities (Model 6) and parents' engagement in math activities (Model 7).

	Model 6		Model 7	
Fixed effect	*B*	95% CI	*B*	95% CI
Intercept	3.52*	[3.41, 3.62]	3.08*	[2.87, 3.29]
Child gender	0.13	[−0.09, 0.34]	−0.15	[−0.41, 0.11]
Parent gender	0.19	[−0.03, 0.41]	0.07	[−0.17, 0.32]
Math beliefs	−0.02	[−0.18, 0.14]	0.07	[−0.12, 0.26]
Parent gender X math beliefs	0.17	[−0.06, 0.40]	–	–
Child age	0.06	[−0.05, 0.17]	−0.11	[−0.24, 0.03]
Parent education	0.07	[−0.05, 0.19]	−0.03	[−0.17, 0.10]
Language used	0.24*	[0.00, 0.47]	−0.16	[−0.48, 0.16]
Non-math activities	–	–	0.55***	[0.42, 0.69]
Literacy beliefs	0.10	[−0.06, 0.26]	−0.06	[−0.25, 0.12]
Math activities	0.48***	[0.37, 0.60]	–	–
Parent gender X literacy beliefs	–	–	−0.22	[−0.48, 0.03]
Random effect	SD		SD	
Family intercept	0.00		0.22	
Site intercept	0.00		0.15	
Residual	0.00		0.55	

*$p < 0.05$; ***$p < 0.001$.

the parent gender gap in math activities (in which mothers engaged in more frequent math activities than fathers) was reduced for parents with strong beliefs about the importance of math for young children. Interestingly, mothers engaged in similar frequencies of math activities regardless of their beliefs about the importance of math, whereas fathers with strong beliefs about the importance of math for young children engaged in more frequent math activities than fathers with less strong beliefs.

Why might this be? Prior research indicates that mothers are generally more involved in young children's daily activities than fathers (Duursma, 2014; Cabrera et al., 2020). As a result, mothers may engage in fairly frequent math activities regardless of how important they believe math skills are, whereas fathers may be motivated to engage in such activities by strong beliefs that math skills are important for children. Along those lines, mothers and fathers may differ in the types of activities they engage in with their child (Hart et al., 2016). Formal activities may require explicit beliefs about the importance of engaging with and teaching children, whereas informal activities may not depend on such strong beliefs. Here, we combined across math activities (due to a limited number of items preventing subanalyses on formal and informal activities), but mothers and fathers may have engaged in qualitatively different activities. Moreover, other parent math beliefs not measured here may affect parents' engagement in math activities. Future work should examine how these relations persist or change when controlling for other parental math beliefs.

Other types of math beliefs (beyond the importance of math) may relate to parents' math engagement and moderate associations between children's and parents' gender and parents' math engagement. Parents may vary in their beliefs about their children's propensity to learn math; their views on their own role and responsibility in helping their children learn math; their expectations for what their children can learn at different ages; their views about appropriate developmental activities for children of specific ages; their beliefs about the fixedness or malleability of math ability; and their gender stereotypes. All not measured here, such beliefs may relate to parents' engagement in math activities with toddlers and account for the different patterns of engagement we observe. Importantly, future work should expand an understanding of how a variety of math beliefs relate to parents' math engagement with their children and potentially interact with parents' and children's gender, to help disentangle these effects. Furthermore, it will be crucial to understand when and where these parental beliefs originate and how they change through children's development, and their consequences for parents' math engagement.

Limitations, conclusions and future directions

Several limitations merit discussion. Our sample, though diverse in educational background, comprised only White, non-Hispanic/Latino and Hispanic/Latino families. Although we saw no differences in parents' math engagement based on the language they spoke (a measure of cultural assimilation; Vigdor, 2009), our findings may not extend to other populations in other contexts. Indeed, parents from different ethnic backgrounds differ in their beliefs and general engagement with their children (e.g., Suizzo, 2007; Keels, 2009), indicating a need for future work on similarities and differences in associations between children's and parents' gender, parents' beliefs about the importance of math, and parent–child math engagement. Furthermore, concurrent associations examined here do not inform on causality. Longitudinal analyses are needed to examine how these relations change over time, and experimental work is needed to determine which types of math activities may specifically support which types of math skills in young children. Relatedly, future work may investigate whether the benefits that children receive from parental math engagement differ based on the gender of the parent involved.

Furthermore, we studied two-year-old toddlers, and observed associations may change with age. Additionally, parents' engagement in math activities may be shaped by other factors not measured here, including, (but certainly not limited to) parents' own math abilities, parents' employment status, children's enrollment in preschool, and the number of other children in the home. We included a control for parents' engagement in non-math activities, which likely would be influenced by some of these factors as well, but future work examining these associations with the addition of critical covariates is warranted. Finally, our measures of parents' beliefs and activities were drawn from self-report questionnaires. As such, the reports may be subject to reporter bias of over-or under-reporting of activities or beliefs. In addition, the math activity questionnaire was composed of only 11 items, which may not capture other math-related activities that parents and children may engage in, parents' use of math talk and math engagement outside of the queried specifically math-related activities, the durations of the activities, and the quality of math content discussed during the activities (see Elliott and Bachman, 2018).

Nonetheless, findings suggest the importance of considering how parents' and children's gender shape parents' beliefs and in turn their math engagement with toddlers. More generally, these results add to our understanding of the factors that relate to the home learning environment, showing that even at very young ages children are exposed to vastly different amounts of math support. Whether and how differences in home math engagement relate to toddlers' early math skills, and how such findings might inform interventions around parents' support of children's early emerging math skills, are critical future directions.

Data availability statement

The original contributions presented in the study are publicly available. This data can be found with DOI 10.17605/OSF.IO/35SVB here: https://osf.io/35svb/.

Ethics statement

The studies involving human participants were reviewed and approved by University of Pittsburgh Institutional Review Board, University of Maryland Institutional Review Board, and New York University Institutional Review Board. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

AS performed the statistical analysis and wrote the first draft of the manuscript. All authors contributed to the conception, design of the study, manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Predicting grade school scientific literacy from aspects of the early home science environment

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Fostering scientific literacy has become an increasingly salient goal as evidence accumulates regarding the early emergence of foundational skills and knowledge in this domain, as well as their relation to long-term success and engagement. Despite the potential that the home context has for nurturing early scientific literacy, research specifying its role has been limited. In this longitudinal study, we examined associations between children's early science-related experiences at home and their subsequent scientific literacy. Following on our previous work, we specifically considered parent causal-explanatory talk, as well as the degree to which parents facilitate access to science-related materials and experiences. A group of 153 children from diverse backgrounds were evaluated across 5 annual waves of data collection from preschool entry (M_{age}=3.41) through first grade (M_{age}=7.92). Results demonstrate that parent invitations for children to explain causal phenomena had strong concurrent relations to scientific literacy but showed little relation to subsequent literacy. In contrast, the broader home science environment at preschool entry, particularly in the form of exposure to science-related activities, predicted scientific literacy over the next 4years. The directionality and specificity of these relations were clarified through the inclusion of measures of cognitive and broader home experiences as controls in regression analyses. Overall, our investigation revealed that exposure to science-related input provided by parents has particularly powerful potential for shaping scientific literacy when children are very young. Implications for parent-focused interventions that promote science literacy are discussed.

KEYWORDS
scientific literacy, preschool science, informal STEM learning, home science environment, parent causal talk

1. Introduction

Given the importance of STEM literacy for personal and societal health and success, considerable discourse and empirical investigation has focused on better equipping children to thrive in these fields. Although the majority of this work has centered around school-aged children or typically children 5 years and up in the USA (e.g., Bathgate et al., 2014; Sha et al., 2016), researchers have increasingly recognized the importance of studying the earliest origins of scientific literacy in younger children (e.g., Alexander et al., 2012; Leibham et al., 2013).

Scientific literacy refers to our understanding of core disciplinary ideas (e.g., physics) and practices (e.g., defining problems, interpreting data), as well as cross cutting concepts (e.g., cause and effect, patterns) as reflected in the current Next Generation Science Standards (NGSS Lead States, 2013). It is now clear that scientific literacy emerges early (Eshach, 2006; Duschl et al., 2007) and that individual and group-level variability in related knowledge and skills is evident prior to school-entry (National Science Board, 2019). Moreover, early scientific knowledge is predictive of success in science throughout grade school (Morgan et al., 2016; Byrnes et al., 2018; Kähler et al., 2020). Better understanding the foundations of scientific literacy is therefore particularly important for discovering ways to support long-term engagement and success in science.

Although the development of evidence-based preschool science curricula (e.g., Peterson and French, 2008; Gelman et al., 2010; Gonzalez et al., 2010) has been an important part of efforts to launch children on positive developmental trajectories in STEM, informal learning contexts have also been highlighted as providing foundational experiences (e.g., Vandermaas-Peeler et al., 2016, 2019; Willard et al., 2019). Of these, the home environment might be particularly impactful in nurturing scientific literacy (e.g., Dearing and Tang, 2010; Schaub, 2015). The current study focuses specifically on parents as a dominant force in shaping the early home environment and a source of experiences potentially relevant to the early emergence and development of children's scientific literacy (Bandura and Walters, 1963; Jacobs and Eccles, 2000; Davis-Kean, 2005). Based on the existing literature, we consider two distinct ways in which parents might exert their influence.

First, we consider the degree to which parents evoke causal explanations in conversations with their children. Causal explanations are descriptions of how or why factors in a system influence each other. When parents scaffold children's consideration of causal explanations, it may support scientific literacy by both contributing directly to conceptual knowledge and by offering opportunities for practicing scientific inquiry processes like hypothesis generation and revision. Several studies have broadly observed the frequency and quality of conversations between parents and their children in a variety of informal science settings (Callanan and Jipson, 2001; Crowley and Galco, 2001; Haden et al., 2014; Van Schijndel and Raijmakers, 2016). For example, Crowley et al. (2001) report that young children are better able to process the causal structure of museum exhibits after exploring them with their parents (see also Willard et al., 2019). Similarly, Callanan et al. (2019) found that parent's causal explanations supported child's systematic exploration of museum exhibits, and that this relationship did not vary by age or gender of the child. Booth et al. (2020) more specifically found that parent's *invitations* for their 3-year-olds to generate causal explanations during free play correlate with the children's concurrent scientific literacy.

Second, we consider the broader home science environment, including access to science-related materials and experiences provided by parents (Westerberg et al., 2022). Empirical research has already linked other specific aspects of the early home learning environment with corresponding domain-specific achievements, such as reading literacy (Sénéchal and LeFevre, 2002; Rodriguez and Tamis-LeMonda, 2011) and math (Hart et al., 2016; Napoli and Purpura, 2018). Despite its potential for similar associations to long-term success (e.g., Bell et al., 2009), the home science environment has received much less attention (Ellis et al., 2022). In one of the few relevant studies, however, Junge et al. (2021) report that home science activities are not only associated with preschooler's scientific knowledge, but that they mediate the association between overall home learning environment (e.g., socioeconomic status, parental interest in science), and child's scientific knowledge (see also Vandermaas-Peeler et al., 2018). Although Booth et al. (2020) only considered the broader home science environment as a control in their analyses of causal talk, they too discovered that it accounted for unique variance in concurrent scientific literacy at 3 years of age.

This work aims to further clarify links between aspects of early experience and emergent scientific literacy by examining four years of longitudinal data beyond the initial wave reported in Booth et al. (2020).We first ask whether associations between parents' causal talk and scientific literacy observed at 3 years of age replicate throughout early childhood. Although Booth et al. (2020) failed to find an association between parent-generated explanations and scientific literacy, we reconsider this theoretically relevant metric in order to evaluate potentially longer-term effects through first grade (7-8-year-olds). We also consider whether the association between parent invitations for their children to explain causal phenomena and scientific literacy observed in Booth et al. (2020) extends to subsequent measurements. These analyses will further clarify the links between aspects of early causally oriented conversations with caregivers and emergent scientific literacy.

We then ask whether broader indicators of the home science environment are potentially foundational to early scientific literacy. In addition to the composite measure of home science used in Booth et al. (2020), we further examine potential divergence in the effects of components thereof. Specifically, we reasoned that science-related experiences (e.g., conducting science experiments) might be more powerful in supporting the development of scientific literacy than exposure to science-related materials (e.g., science books), given that the latter are likely to be useful only to the extent that they are incorporated into the former. This might be especially true for very young children who are limited in their ability to productively explore science-related materials on their own. We suspect that the home environment will become relatively less predictive of scientific literacy as children are increasingly exposed to science in a variety of other contexts (e.g., preschool) and come to exert more control over which activities they engage in (Maccoby 1984; Bergin 2016).

Throughout, we capitalize on the longitudinal nature of the data to achieve greater precision in our conclusions. Specifically, we clarify the directionality of effects by controlling for initial scientific literacy. We also clarify the specificity of observed associations by controlling for general cognitive skills and broader (non-science) cognitive stimulation in the home, and by considering contrastive predictions to math and reading skills.

2. Methods

2.1. Participants

An *a priori* power analysis using G*Power software (Faul et al., 2007) suggested a sample size of 120–150 children for our longitudinal observational study. As part of a larger longitudinal study, 153 children were recruited from a database of families interested in research from Austin, Texas and surrounding areas (81 female, $M_{age} = 3.41$ years, SD = 0.26, range = 3.01–3.92). Child participants were described by their caregivers as proficient in English and absent of any diagnosed developmental delay or disorder. At the first session, eight additional children were excluded based on their inability to follow instructions due to inadequate English knowledge or behavioral noncompliance. The sample was demographically diverse across race, ethnicity, and maternal education (see Table 1). At the second wave of data collection, 120 (64 female, $M_{age} = 4.59$ years, SD = 0.26, range = 3.66–5.09) remained in the study, at the third wave 112 (61 female, $M_{age} = 5.02$ years, SD = 0.23, range = 5.02–5.92) remained, at the fourth wave 88 (43 female, $M_{age} = 6.78$ years, SD = 0.23, range = 6.04–7.66) remained, and at the final wave 87 (47 female, $M_{age} = 7.92$ years, SD = 0.28, range = 7.12–8.51). Throughout these years of assessment, attrition was primarily due to families moving out of town or our inability to re-establish contact. Data collection at the fourth wave was also substantially disrupted by the COVID-19 pandemic, resulting in a spike in attrition and an eventual shift to virtual data collection (see Table 2).

2.2. Procedure

One wave of data was collected each year, for 5 years, and each wave included between two and five sessions of testing. Sessions were video-recorded and later coded offline. Each session included between three to six tasks (always presented in the same order) and lasted between 30 and 60 min. All Wave 1, 2, and 3 sessions were conducted in a laboratory setting except for the very first session of Wave 1 which was conducted at a local science museum. Although testing began in the laboratory for Wave 4, the global pandemic necessitated that we shift to virtual format. Wave 5 was also conducted virtually. After each session, caregivers received financial compensation and, if the session was run in person, the child was also given a book.

2.3. Measures

Our investigation included measures of parent causal talk and the broader home science environment, as well as children's scientific literacy and general cognitive ability. See Table 3 for measures used at each wave.

2.3.1. Home environment

2.3.1.1. Parent causal talk

Parent–child dyads played freely with toys affording causal explanations at Waves 1 (sink-float task in the lab and a launcher museum exhibit that involved building and testing airplanes), 2 (Hasbro's Mouse Trap™ game) and 3 (balance scale task). Based on pilot observations and timing constraints, participants were allotted 10 min to play with each set of toys. They were given no specific instructions about how to interact with the toys and were only told to let the experimenter know if they wanted to stop early. The 10 min of play were coded offline and broken into 60 s windows. For each window, coders indicated if the parent (1) produced a causal explanation, (2) invited the child to explain a causal phenomenon, and (3) provided any other causally relevant utterance. Utterances coded as causal explanations often included "because" or "if, then" statements, such as, "If I put the ball here, then this will make it fall." Likewise, utterances coded as causal invitations often contained "why" or "how," such as, "Why do you think that one sank?." See Table 4 for more examples of utterances and how they were coded.

For each of these causal constructs, the proportion of 60 s windows (out of the total maximum of 10) in which parents produced at least one utterance of each target construct was calculated. Utterances were coded as causally oriented even if the information

TABLE 1 Participant demographics (in percentages) across 5years of data collection.

		Wave 1 (n=153)	Wave 2 (n=120)	Wave 3 (n=112)	Wave 4 (n=88)	Wave 5 (n=87)
Race	White/Caucasian	73.9	74.2	78.4	78.4	80.5
	Black/African American	13.1	12.5	7.2	4.5	4.6
	Asian/Asian American	2.6	1.7	0.9	2.3	2.3
	Mixed Race/Other	10.5	11.7	13.5	14.8	12.6
Ethnicity	Non-Hispanic/Latino	69.9	72.5	68.5	70.5	70.1
	Hispanic/Latino	30.1	27.5	31.5	29.5	29.9
Maternal Education	No more than high school	27.5	20.9	18.0	12.5	14.9
	Technical or Associate's degree	6.5	6.7	6.3	6.8	3.4
	Bachelor's degree	38.6	44.2	46.8	46.6	49.4
	Master's degree	18.9	20.0	19.8	22.7	24.1
	Advanced degree	8.5	8.3	9.0	11.4	8.0

TABLE 2 Missing data (in percentages) and reasons for missingness.

	Task	% Missing	Top 3 Reasons for Missingness (*n*)†
Wave 1	Causal Talk	17.65	Technical ($n = 17$), Attrition ($n = 10$)
	Scientific Literacy-Lens	3.27	Attrition ($n = 4$), Behavioral ($n = 1$)
	Home Science	3.92	Incomplete ($n = 6$)
	StimQ-P	18.30	Attrition ($n = 27$), Incomplete ($n = 1$)
	Causal Talk	25.49	Attrition ($n = 39$)
	NIH-ECB		
	PVT	1.31	Attrition ($n = 1$), Behavioral ($n = 1$)
	FL	24.18	Attrition ($n = 24$), Failed Training ($n = 7$), Behavioral ($n = 5$)
	DCCS	32.68	Attrition ($n = 29$), Failed Training ($n = 11$), Behavioral ($n = 8$)
	PS	39.47	Attrition ($n = 28$), Failed Training ($n = 15$), Technical ($n = 15$)
Wave 2	Scientific Literacy-Lens	26.97	Attrition ($n = 33$), Behavioral ($n = 7$)
	Home Science	22.88	Attrition ($n = 34$), Incomplete ($n = 1$)
	NIH-ECB		
	PVT	21.57	Attrition ($n = 33$)
	FL	28.10	Attrition ($n = 40$), Behavioral ($n = 2$), Failed Training ($n = 1$)
	DCCS	31.37	Attrition ($n = 42$), Behavioral ($n = 5$), Failed Training ($n = 1$)
	PS	35.29	Attrition ($n = 42$), Failed Training ($n = 9$), Behavioral ($n = 3$)
Wave 3	Causal Talk	32.68	Attrition ($n = 46$), Technical ($n = 4$)
	Scientific Literacy-Lens	34.64	Attrition ($n = 41$), Behavioral ($n = 8$), Technical ($n = 4$)
	Scientific Literacy-SLA	36.60	Attrition ($n = 56$)
	Home Science	46.05	Attrition ($n = 50$), Incomplete ($n = 20$), Experimenter Error ($n = 1$)
Wave 4	Scientific Literacy-SLA	49.67	Attrition ($n = 74$), Behavioral ($n = 2$)
	Scientific Literacy-TNSci	43.79	Attrition ($n = 65$), Incomplete ($n = 2$)
	Home Science	50.33	Attrition ($n = 76$), Incomplete ($n = 1$)
Wave 5	Scientific Literacy-SKI	50.34	Attrition ($n = 75$)
	Scientific Literacy-TNSci	44.74	Attrition ($n = 65$), Behavioral ($n = 2$), Incomplete ($n = 1$)
	Home Science	58.82	Attrition ($n = 80$), Incomplete ($n = 10$)
	TNMath	60.53	Attrition ($n = 78$), Incomplete ($n = 13$), Behavioral ($n = 1$)
	NIH TORRT	50.98	Attrition ($n = 77$), Incomplete ($n = 1$)

NIH-ECB = NIH Toolbox Early Cognition Battery; PVT = Picture Vocabulary Test; FL = Flanker Inhibitory Control and Attention Test; DCCS = Dimensional Change Card Sort Test; PS = Picture Sequence Memory Test; StimQ-P = StimQ-Preschool; Lens = Lens on Science; SLA = Science Learning Assessment; SKI = Science Knowledge Inventory; NIH TORRT = NIH Toolbox Oral Reading Recognition Test; TNSci = TerraNova Science; TNMath = TerraNova Math; Home Science = Home Science Environment.
†Total $N = 153$. Attrition within a given wave of data collection was possible given that tasks were administered across multiple sessions.

provided in that utterance was not technically correct (e.g., referencing size instead of density/weight). The proportion of windows in which parents specifically produced an explanation or an invitation served as the key dependent variables. Note that because two play sessions were implemented at Wave 1 (in the lab and museum), final proportions were attained by averaging across contexts. An additional research assistant independently coded 20 percent of the co-play sessions. Although reliability was generally good (all inter-class correlations >0.75), discrepancies were jointly reviewed to arrive at full consensus.

2.3.1.2. Home science environment

A parent survey was administered at each wave of data collection asking about the number of science-themed books, toys, and apps/computer games available in the home. No specific examples were provided for these home resources and it was left to the caregiver to determine what counted as "science." These responses were each coded into bins (1–5 = 1, 6–20 = 2, 21–50 = 3, and 50+ = 4) and then summed across types to calculate a 'materials' score ranging from 0 to 12. Parents were also asked about the frequency (on a 7-point scale with 0 = never and 6 = almost every day) with which they participate in science activities (e.g., like reading science books and conducting experiments) with their child, as well as how often they visit science fairs or museums with their children (0 = never, 6 = every week or two). These were then summed into an 'activities' score ranging from 0 to 12. The material and activities scores were then summed into the total home science environment score ranging from 0 to 24. See Meyer (1990) and Jacobs and Bleeker (2004) for similar assessments.

TABLE 3 Measures used at each timepoint of data collection.

Construct	Measure	Wave 1	Wave 2	Wave 3	Wave 4	Wave 5
Parent input	Parent Causal Talk	✓	✓	✓		
Broader home environment	Home Science Environment Survey	✓	✓	✓	✓	✓
Scientific literacy	Lens on Science	✓	✓	✓		
	SLA			✓	✓	
	TerraNova Science				✓	✓
	SKI					✓
Cognitive simulation and ability	StimQ-Preschool	✓				
	NIH-ECB	✓	✓			
	TerraNova Math					✓
	NIH TORRT					✓

SLA, Science Learning Assessment; SKI, Science Knowledge Inventory; NIH-ECB, NIH Toolbox Early Cognition Battery; NIH TORRT, NIH Toolbox Oral Reading Recognition Test.

TABLE 4 Parent causal talk: example utterances for code types.

Code type	Example utterances
Causal explanations	This one is heavier so that's why it goes to the bottom. The higher the pressure is, the further it will fly. I think that tail made it a little heavy. It did not go quite as far, huh?
Causal invitations	Why do you think they sink to the bottom? Why is it floating? How are you going to make it fly?
(Other causal talk)	Which ones do you think will sink? What happens if you put it that way? The ones on the bottom are heaviest. Were you adjusting the little knob over there before? You think we should try a smaller tail? Is it aimed okay? That one sinks. See, it goes straight to the bottom.

2.3.1.3. Cognitive stimulation

The StimQ-Preschool (Mendelsohn et al., 1999) scale measures cognitive stimulation present in the home environment of children ages 3 to 6. Questions focus on the availability of learning materials, frequency of reading, parental involvement, and parent verbal responsivity with scores ranging from 0 to 89. This measure was not included in the design of the original longitudinal study but was collected on the same sample at Wave 1 for a related student project. It is included here as a useful control in assessing the specificity of effects.

2.3.2. Scientific literacy

Different developmentally appropriate measures of scientific literacy were utilized at each measurement time point. More information on the scientific literacy measures is available on OSF.[1]

2.3.2.1. Lens on science

Lens on Science (Greenfield, 2015) is an adaptive computerized measure developed for children aged 3 to 5 that aims to assess all the scientific literacy components specified in the U.S. national science education guidelines (National Research Council, 2012). It takes approximately 15 min to administer, during which 35 to 40 items are presented (from a bank of 498 items). The items represent the three broad domains of life, earth and space, and physical and energy science, as well as eight core science practices (observing, describing, comparing, questioning, predicting, experimenting, reflecting, and cooperating). Children are instructed to respond to an item by selecting one of several images on a tablet touchscreen. Upon completion, each child received a standard item response theory (IRT) ability score ranging from −3 to 3. High reliability of 0.87 is reported by Greenfield (2015).

2.3.2.2. Science learning assessment (SLA)

The SLA (Samarapungaven et al., 2009) is designed for kindergarten students kindergarten students (ages 5 and 6) and consists of 24 items broken into two subtests: the Scientific Inquiry Processes subtest and the Live Science Concepts subtest. The Scientific Inquiry Processes subtest asks about children's understanding of how science is conducted (e.g., making predictions, understanding simple scientific tools) and children select among three possible answers presented visually and verbally. The Life Science Concepts subtest asks about children's knowledge of living things and the physical world in multiple choice format (e.g., choosing the correct name of an animal that corresponds to the picture shown) and in free response questions (e.g., mechanism in which insects move). Scores range from 0 to 38. Internal reliability is reported as 0.79 by Samarapungavan et al. (2009).

2.3.2.3. TerraNova science subtest (third edition)

TerraNova Science Subtest (CTB/McGraw-Hill LLC, 2010) is a standardized norm-referenced achievement test that taps into knowledge in core science content areas (life, earth, physical science, and scientific inquiry) for students in grade school (K-12 in the U.S.). The test consists of 20 multiple choice questions and its raw scores range from 0 to 20.

1 https://osf.io/y98g5

TABLE 5 Correlations for scientific literacy measures at Wave 3, 4, and 5.

		1	2	3	4	5	6
Scientific literacy	1. Lens3	–					
	2. SLA3	0.46**	–				
	3. SLA4	0.38**	0.49**	–			
	4. TNSci4	0.35*	0.36**	0.47**	–		
	5. SKI	0.41*	0.45**	0.42*	0.37*	–	
	6. TNSci5	0.38*	0.43**	0.44**	0.55**	0.32*	–

Lens, Lens on Science; SLA, Science Learning Assessment; TNSci, TerraNova Science Subtest; SKI, Science Knowledge Inventory. The number following the task abbreviation is the measurement wave. $^{**}p<0.01$, $^{*}p<0.05$.

2.3.2.4. Science knowledge inventory (SKI)

Administered at the last wave, the SKI (Koerber and Osterhaus, 2019) consists of 30 multiple-choice items equally drawn from three areas: experimentation, data interpretation, and understanding the nature of science (e.g., what scientists do, what scientists ask). For each item, the experimenter reads a brief description of a character who wishes to find something out about science. Children choose their answers to each item from among three illustrated options. Internal reliability of 0.78 is reported by Koerber and Osterhaus (2019). Full measure is available on the original authors' OSF.[2]

2.3.3. Cognitive ability

2.3.3.1. NIH toolbox early childhood cognition battery (ECB)

The ECB (Bauer and Zelazo, 2014) is a highly reliable measure of children's overall cognitive functioning, consisting of four tasks: the Dimension Change Card Sort Test, (assessing cognitive flexibility), the Flanker Inhibitory Control and Attention Test (assessing inhibitory control), the Picture Sequence Memory Test (assessing episodic memory), and the Picture Vocabulary Test (assessing receptive vocabulary). Composite age-adjusted scaled scores (with a mean of 100) were calculated after imputing values for missing component tasks. This task was used to control for general cognitive abilities in regression analyses.

2.3.3.2. TerraNova math subtest (third edition)

As with TerraNova Science Subtest, the Math Subtest (CTB/McGraw-Hill LLC, 2010) is a norm-standardized achievement test of math ability that includes 47 questions. This test was used as a contrast case in specifying the precision of associations to scientific literacy in our analyses. Raw scores range from 0 to 47.

2.3.3.3. NIH toolbox oral reading recognition test (TORRT)

The TORTT (Gershon et al., 2013) is an adaptive test that measures children's pronunciation of individual printed words and naming and recognition of individual printed letters presented on a tablet." Raw scores range from 0 to 20. This test was also used as a contrast case in specifying the precision of associations to scientific literacy in our analyses.

2 https://osf.io/b5mr8

3. Results

We first evaluated whether missing data caused systematic variability across key demographic factors or measurements. Little's Test (Little, 1988) was not significant, suggesting that our data were missing completely at random (MCAR), χ^2 (3441) = 3450.59, $p = 0.404$. To address missing data in a maximally unbiased manner, we conducted 100 iterations of multiple imputation including our home science environment and scientific literacy measures. Demographic and cognitive variables that correlated highly ($r > 0.40$) with our key measures (and had no more than 25% missingness themselves) were also included as auxiliary variables in the imputation (see Johnson and Young, 2011). Child gender was included in these preliminary analyses of demographic variables and did not correlate with any of our key variables, including parent causal talk, and hence was not included in the current analysis.

After imputation, we combined our scientific literacy scores into a single composite score for waves where multiple measures were available (i.e., Waves 3, 4, and 5). This decision was based on the face validity of conceptual equivalence across our scientific literacy measures and the significant correlations between them at each measurement wave (see Table 5). Next, we conduct a series of bivariate correlation and multiple regression analyses to investigate our major research questions.

3.1. Does parent causal talk relate to scientific literacy?

As a first step, we examined descriptive statistics and bivariate correlations between parent causal talk and scientific literacy measures. As expected, and consistent with Booth et al. (2020), parent invitations for children to explain causal phenomena at Wave 1 had a significant positive association with children's concurrent scientific literacy ($r = 0.24$, $p = 0.006$). Although parent invitations to explain at Waves 2 and 3 failed to correlate with either concurrent or subsequent scientific literacy, parent invitations to explain at Wave 1 did also correlate with scientific literacy one year later ($r = 0.24$, $p = 0.012$). In contrast, parent-produced causal explanations failed to correlate with scientific literacy in any analysis (see Table 6), which is also consistent with Booth et al. (2020).

Given that (1) parent invitations-to-explain correlated with scientific literacy at Wave 1 and (2) scientific literacy was stable across Wave 1 and 2, it was important to clarify whether the observed association between parent invitations-to-explain at Wave 1 and

TABLE 6 Bivariate correlations for parent talk and scientific literacy.

		Parent causal talk						*M (SD)*
		Wave 1		Wave 2		Wave 3		
		Exp	Invite	Exp	Invite	Exp	Invite	
Scientific Literacy†	Wave 1	0.028	0.24*	0.05	0.11	−0.05	0.00	0.36 (1.00)
	Wave 2	−0.03	0.24*	0.020	0.12	−0.06	0.15	1.51 (1.00)
	Wave 3	−0.01	0.16	0.16	0.20	0.05	0.20	−0.14 (0.97)
	Wave 4	−0.01	0.14	0.09	0.18	0.08	0.11	−0.22 (1.06)
	Wave 5	−0.04	0.08	0.02	0.10	0.04	0.15	−0.01 (1.00)
	M (SD)	0.13 (0.13)	0.09 (0.11)	0.17 (0.17)	0.08 (0.15)	0.14 (0.17)	0.15 (0.13)	

Exp, Casual Explanations; Invite, Invitations to Explain Causal Phenomenon. †Scientific Literacy at Wave 3, 4, and 5 is a standardized composite score but is a single score at Wave 1 and Wave 2. ** $p < 0.01$, * $p < 0.05$.

TABLE 7 Bivariate correlations for home science environment and scientific literacy.

		Home Science Environment				
		Wave 1	Wave 2	Wave 3	Wave 4	Wave 5
Scientific literacy†	Wave 1	0.18*	0.23*	0.11	0.22*	0.13
	Wave 2	0.30**	0.26*	0.18	0.25*	0.19
	Wave 3	0.31**	0.23*	0.20	0.24	0.19
	Wave 4	0.19	0.34**	0.20	0.38*	0.29
	Wave 5	0.15	0.32**	0.31*	0.33*	0.37*
	M (SD)	12.33 (3.72)	13.94 (3.90)	14.18 (3.76)	12.76 (4.21)	13.42 (5.08)

†Scientific Literacy at Wave 3, 4, and 5 is a standardized composite score but is a single score at Wave 1 and Wave 2. ** $p < 0.01$; * $p < 0.05$.

scientific literacy at Wave 2 was truly predictive (rather than merely a spurious byproduct of these other two associations). We therefore conducted a multiple regression analysis, controlling for baseline (Wave 1) scientific literacy scores. Consistent with an early association carried forward by stability in measurement of scientific literacy, parent invitations were no longer predictive of scientific literacy scores at Wave 2 in this analysis, $B = 0.801$ (SE = 0.718), $p = 0.265$.

3.2. Does the home science environment relate to scientific literacy?

In parallel with our analyses of aspects of parent causal talk, our first step in investigating relations between home environment and scientific literacy was to calculate descriptive statistics and bivariate correlations between home science environment and scientific literacy scores. We observed significant associations between home science environment at Wave 1 ($r = 0.18$, $p = 0.028$) and Wave 2 ($r = 0.30$, $p < 0.001$), and Wave 3 ($r = 0.31$, $p < 0.001$) scientific literacy scores. The home science environment at Wave 2 was significantly positively related to scientific literacy at all waves, with the strongest associations observed at Wave 4 ($r = 0.34$, $p = 0.003$) and Wave 5 ($r = 0.32$, $p = 0.004$). Although later home science environment scores were less strongly correlated with scientific literacy scores in general, science environment scores at Waves 3, 4, and 5 were significantly associated with scientific literacy at Wave 5 (see Table 7).

We next evaluated whether significant correlations observed across waves of data collection truly reflected predictive relations (as opposed to residual effects of the relative stability of scientific literacy). To this end, we first ran a multivariate regression analysis with home science environment at Wave 1 predicting scientific literacy at Waves 1, 2, and 3, while controlling for baseline (Wave 1) scientific literacy (see Table 8, Model 1). Wave 1 home science environment continued to predict subsequent scientific literacy scores at Wave 2, $B = 0.05$ (SE = 0.02), $p < 0.01$ and Wave 3, $B = 0.06$ (SE = 0.10), $p < 0.01$, over and above baseline scientific literacy. To explore the possibility that the observed relation between home science environment and subsequent scientific literacy was due to a common reliance on broad cognitive skills, we ran a follow-up regression analysis including NIH-ECB as an additional predictor. Indeed, when controlling for baseline cognitive skills, the Wave 1 home science environment no longer accounted for a significant amount of variance in Wave 2 scientific literacy scores, $B = 0.04$ (SE = 0.02), $p = 0.076$, although a trend was still evident. The home science environment did, however, predict Wave 3 scientific literacy scores, $B = 0.05$ (SE = 0.02), $p < 0.05$ over and above baseline cognitive skills (see Table 8, Model 2).

We then turned our attention to the relation between Wave 2 home science environment and subsequent scientific literacy scores. Again, we added baseline scientific literacy score as a predictor in the regression analysis (see Table 9, Model 1) and followed up with adding baseline cognitive skills as an additional predictor (Table 9, Model 2). When controlling for Wave 2 scientific literacy scores, we see Wave 2 home science environment predicting Wave 4 scientific literacy scores, $B = 0.06$ (SE = 0.03), $p < 0.05$, and trending toward significance for Wave 5 but not at Wave 3. When Wave 2 cognitive skills are added into the regression, the Wave 2 home science environment no longer accounts for significant variance in any subsequent scientific literacy score, although trends remain near significance for Waves 4 and 5.

TABLE 8 Multivariate regression analyses for home science environment at Wave 1 predicting scientific literacy at Wave 2 and 3.

Outcome	Predictor	Unstandardized		Standardized	*t*	*p*	95% CI		*sr*
		B	SE	β			*LL*	*UL*	
Model 1: Controlling for baseline scientific literacy									
SciLit2†	Intercept	0.71	0.25	−0.06	2.82	0.005	0.22	1.20	
	HomeSci1	0.05	0.02	0.18	2.58	0.010	0.01	0.09	0.19
	Lens1	0.62	0.01	0.64	8.05	<0.001	0.47	0.77	0.61
SciLit3	Intercept	−1.04	0.70	0.02	−3.66	<0.001	−1.60	−0.48	
	HomeSci1	0.06	0.10	0.26	2.68	0.007	0.02	0.10	0.23
	Lens1	0.44	0.01	0.43	5.39	<0.001	0.28	0.60	0.45
Model 2: Controlling for baseline scientific literacy and cognitive skills									
SciLit2	Intercept	−0.58	0.55	−0.07	−1.06	0.291	−1.65	0.49	
	HomeSci1	0.04	0.20	0.12	1.78	0.076	0.00	0.08	0.13
	Lens1	0.51	0.09	0.52	5.85	<0.001	0.34	0.69	0.43
	NIH-ECB1	0.02	0.01	0.22	2.64	0.008	0.00	0.03	0.17
SciLit3	Intercept	−1.89	0.63	0.01	−2.89	0.004	−3.17	−0.61	
	HomeSci1	0.05	0.02	0.21	2.14	0.032	0.00	0.10	0.18
	Lens1	0.37	0.09	0.33	3.93	<0.001	0.18	0.55	0.32
	NIH-ECB1	0.01	0.01	0.18	1.46	0.145	0.00	0.02	0.12

SciLit, Scientific Literacy; Lens, Lens on Science; HomeSci, Home Science Environment; NIH-ECB, NIH Toolbox Early Childhood Cognition Battery; CI, confidence interval; LL, lower limit; UL, upper limit; sr, semi-partial (part) correlation. The number following the task abbreviation is the measurement wave. †SciLit at Wave 3 is a standardized composite score but is a single score at Wave 2.

Although the analyses reported thus far are consistent with at least some truly predictive relations between the early home science environment and subsequent scientific literacy, it is still possible that the reciprocal relation exists whereby a child's level of scientific literacy might shape their subsequent home literacy environment. Some significant bivariate correlations seen in Table 7 were consistent with this possibility. Specifically, Wave 1 scientific literacy was positively correlated with the home science environment at Waves 2 and 4 (see Table 7). Also, Wave 2 scientific literacy was correlated with home science environment at Wave 4, and Wave 4 scientific literacy was correlated with home science at Wave 5. To clarify the nature of these associations, we ran additional regression analysis with home science environment as the outcome and scientific literacy as the predictor, controlling for baseline home science environment. None of the observed reciprocal relations held under these circumstances (all $ps > 0.10$).

In further exploratory analyses, we examined the materials and activities subcomponents of the home science environment score separately. As can be seen in Table 10, significant bivariate correlations were evident between science *activities* at Wave 1 and scientific literacy measured concurrently at all subsequent waves. Science *materials*, in contrast, only correlated relatively weakly with scientific literacy at the second wave of measurement. These associations reversed somewhat when the home science environment at Wave 2 was instead considered. Here, science activities only correlated significantly with scientific literacy at Wave 4 and 5 while science materials correlated significantly with all waves of scientific literacy, although only at a trend level for Wave 3. Correlations between later measures of home science activities and materials with scientific literacy were only sporadically observed.

Importantly, when submitted to regression analyses including baseline scientific literacy (see Table 11, Model 1), all associations between science activities at 3 years and subsequent scientific literacy held (albeit at only a trend level for Wave 5). Associations further weaken when cognitive skill is added as a control (see Table 11, Model 2), although scientific activities at 3 years still account for significant variance in scientific literacy at Wave 3, and trend toward doing so at Wave 2 as well.

In contrast, no predictive relations between access to science materials and subsequent scientific literacy hold when baseline scientific literacy is included as a control (all $ps > 0.10$). None of the few reciprocal correlations between early scientific literacy and later home science activities or materials observed in Table 10 hold in regression analyses when controlling for baseline levels of the corresponding aspect of the home science environment (all $ps > 0.10$).

3.3. How specific are observed relations between the home science environment and scientific literacy?

Given that there are many ways that children's home environment might contribute to the development of their scientific literacy, it was important to distinguish our measure of the home science environment from the broader richness of the home environment. We therefore added the StimQ-P, the more general measure of the home learning environment, as another predictor into our regression models. While scores on the StimQ-P positively correlated with our measure of the home science environment at Wave 1 ($r = 0.53$, $p < 0.001$), it was not to the degree to cause a collinearity threat. The StimQ-P did not significantly predict scientific literacy at Wave 2,

TABLE 9 Multivariate regression analyses for home science experience at Wave 2 predicting scientific literacy at Waves 3, 4, and 5.

Outcome	Predictor	Unstandardized		Standardized	*t*	*p*	95% CI		*sr*
		B	SE	β			*LL*	*UL*	
Model 1: Controlling for baseline scientific literacy									
SciLit3	Intercept	−1.31	0.33	0.08	−3.95	<0.001	−1.96	−0.66	
	HomeSci2	0.02	0.02	0.10	0.76	0.446	−0.03	0.06	0.07
	Lens2	0.59	0.09	0.59	6.70	<0.001	0.42	0.77	0.59
SciLit4	Intercept	−1.86	0.42	0.11	−4.44	<0.001	−2.68	−1.03	
	HomeSci2	0.06	0.03	0.21	2.00	0.046	0.00	0.11	0.20
	Lens2	0.55	0.11	0.49	4.91	<0.001	0.33	0.77	0.51
SciLit5	Intercept	−1.53	0.39	0.08	−3.91	<0.001	−2.30	−0.76	
	HomeSci2	0.05	0.03	0.14	1.87	0.063	0.00	0.10	0.18
	Lens2	0.53	0.11	0.51	4.97	<0.001	0.33	0.74	0.52
Model 2: Controlling for baseline scientific literacy and cognitive skills									
SciLit3	Intercept	−2.24	0.69	0.06	−3.26	<0.001	−3.58	−0.89	
	HomeSci2	0.02	0.02	0.09	0.71	0.481	−0.03	0.06	0.06
	Lens2	0.52	0.11	0.51	4.93	<0.001	0.31	0.72	0.43
	NIH-ECB2	0.01	0.01	0.13	1.51	0.131	0.00	0.02	0.12
SciLit4	Intercept	−2.90	0.82	0.10	−3.55	<0.001	−4.51	−1.30	
	HomeSci2	0.05	0.03	0.20	1.94	0.054	0.00	0.11	0.19
	Lens2	0.47	0.14	0.40	3.41	<0.001	0.20	0.73	0.36
	NIH-ECB2	0.01	0.01	0.15	1.37	0.172	−0.01	0.03	0.13
SciLit5	Intercept	−2.09	0.77	0.07	−2.70	0.007	−3.60	−0.57	
	HomeSci2	0.05	0.03	0.13	1.81	0.072	0.00	0.09	0.17
	Lens2	0.48	0.12	0.45	3.88	<0.001	0.24	0.73	0.40
	NIH-ECB42	0.01	0.01	0.09	0.08	0.422	−0.01	0.02	0.07

SciLit, Scientific Literacy (composite score); Lens, Lens on Science; HomeSci, Home Science Environment; NIH-ECB, NIH toolbox Early Childhood Cognition Battery; CI, confidence interval; LL, lower limit; UL, upper limit; sr, semi-partial (part) correlation. The number following the task abbreviation is the measurement wave.

TABLE 10 Bivariate correlations for home science activities, home science materials, and scientific literacy.

		Home science environment									
		Wave 1		Wave 2		Wave 3		Wave 4		Wave 5	
		Act	Mat	Act	Mat	Act	Mat	Act	Mat	Act	Mat
Scientific Literacy†	Wave 1	0.18*	0.11	0.13	0.22*	0.00	0.17	0.13	0.18	0.05	0.15
	Wave 2	0.30**	0.19*	0.18	0.23*	0.03	0.25*	0.14	0.21	0.06	0.23
	Wave 3	0.37**	0.15.	0.15	0.21	0.16	0.17	0.33*	0.06	0.19	0.12
	Wave 4	0.29**	0.02	0.28*	0.27*	0.17	0.15	0.25	0.23	0.22	0.24
	Wave 5	0.26*	−0.01	0.26*	0.26*	0.21	0.27*	0.23	0.25	0.22	0.35*

Act, Activity; Mat, Material. †Scientific Literacy at Wave 3, 4, and 5 is a standardized composite score but is a single score at Wave 1 and Wave 2. ** $p<0.01$, * $p<0.05$.

$B=0.02$ (SE = 0.02), $p=0.409$, nor Wave 3, $B=-0.01$ (SE = 0.02), $p=0.683$. Home science environment (as well as the activities component alone) at Wave 1, on the other hand, continued to predict scientific literacy at Wave 3, $B=0.06$ (SE = 0.03), $p<0.05$, over and above StimQ-P (see Table 12). Because we did not collect StimQ-P scores at the second wave of measurement, we used Wave 1 scores as our closest approximation in regressions predicting scientific literacy from the Wave 2 home science environment. Here, the StimQ-P again failed to significantly predict scientific literacy at any wave, while the home science environment composite at Wave 2 did predict scientific literacy at Wave 5 (over and above StimQ-P), $B=0.06$ (SE = 0.03), $p<0.05$. In addition, excluding the home science environment factor entirely (i.e., leaving only StimQ-P in the regression model along with baseline scientific literacy) failed to yield any significant predictions to scientific literacy at any time point.

Lastly, we considered whether aspects of the home science environment specifically predict scientific literacy, as opposed to more generally predicting achievement in a domain-general way. To this

TABLE 11 Multivariate regression analyses for home science activity at Wave 1 predicting scientific literacy at Waves 2, 3, 4, and 5.

Outcome	Predictor	Unstandardized		Standardized	*t*	*p*	95% CI		*sr*
		B	SE	*β*			LL	UL	
Model 1: Controlling for baseline scientific literacy									
SciLit2[†]	Intercept	0.71	0.24	−0.05	3.01	0.00	0.25	1.18	
	HomeAct1	0.08	0.03	0.19	2.71	0.01	0.02	0.14	0.19
	Lens1	0.62	0.08	0.64	8.06	<0.001	0.47	0.77	0.61
SciLit3	Intercept	−1.20	0.27	0.03	−4.45	<0.001	−1.73	−0.67	
	HomeAct1	0.121.	0.03	0.29	3.51	<0.001	0.05	0.19	0.28
	Lens1	0.43	0.08	0.42	5.37	<0.001	0.27	0.59	0.44
SciLit4	Intercept	−1.12	0.34	0.08	−3.26	0.00	−1.79	−0.44	
	HomeAct1	0.10	0.04	0.22	2.27	0.02	0.01	0.18	0.21
	Lens1	0.48	0.11	0.41	4.61	<0.001	0.28	0.69	0.45
SciLit5	Intercept	−0.80	0.34	0.04	−2.35	0.02	−1.48	−0.13	
	HomeAct1	0.08	0.04	0.15	1.91	0.06	0.00	0.16	0.18
	Lens1	0.38	0.10	0.35	3.81	<0.001	0.18	0.57	0.38
Model 2: Controlling for baseline scientific literacy and cognitive skills									
SciLit2	Intercept	−1.03	0.74	−0.07	−1.39	0.17	−2.49	0.43	
	HomeAct1	0.04	0.04	0.10	1.24	0.22	−0.03	0.11	0.08
	Lens1	0.50	0.09	0.51	5.57	<0.001	0.32	0.67	0.41
	NIH-ECB1	0.01	0.01	0.20	2.49	0.01	0.00	0.03	0.16
	StimQ1	0.02	0.02	0.08	0.96	0.34	−0.02	0.05	0.07
SciLit3	Intercept	−1.62	0.92	0.02	−1.76	0.08	−3.43	0.19	
	HomeAct1	0.12	0.04	0.26	2.92	0.00	0.04	0.20	0.24
	Lens1	0.38	0.10	0.34	4.02	<0.001	0.19	0.57	0.32
	NIH-ECB1	0.01	0.01	0.15	1.30	0.19	0.00	0.02	0.10
	StimQ1	−0.01	0.02	−0.01	−0.51	0.61	−0.05	0.03	−0.05
SciLit4	Intercept	−2.65	1.07	0.06	−2.48	0.01	−4.75	−0.55	
	HomeAct1	0.06	0.05	0.13	1.30	0.19	−0.03	0.16	0.12
	Lens1	0.37	0.12	0.27	3.13	0.00	0.14	0.60	0.28
	NIH-ECB1	0.01	0.01	0.24	1.68	0.09	0.00	0.03	0.15
	StimQ1	0.01	0.02	0.04	0.44	0.66	−0.03	0.05	0.04
SciLit5	Intercept	−1.51	1.09	0.03	−1.39	0.17	−3.65	0.63	
	HomeAct1	0.07	0.05	0.12	1.45	0.15	−0.03	0.16	0.14
	Lens1	0.31	0.11	0.15	2.81	0.01	0.09	0.53	0.26
	NIH-ECB1	0.01	0.01	0.20	1.43	0.15	0.00	0.03	0.13
	StimQ1	−0.00	0.02	−0.06	−0.30	0.76	−0.05	0.039	−0.03

SciLit, Scientific Literacy; Lens, Lens on Science; HomeAct, Home Science Activities; NIH-ECB, NIH toolbox Early Childhood Cognition Battery; CI, confidence interval; StimQ, StimQ-Preschool; LL, lower limit; UL, upper limit; sr, semi-partial (part) correlation. The number following the task abbreviation is the measurement wave. [†]Scientific Literacy at Wave 3, 4, and 5 is a standardized composite score but is a single score at Wave 1 and Wave 2.

end, we conducted a bivariate correlation analysis with measures of two conceptually distinct academic domains (the TerraNova Math subtest and the NIH Oral Reading Recognition task) taken at the last measurement time point. No associations between these outcomes and any aspect of early input (i.e., parent causal invitations, the home science environment composite, materials or activities) were detected (see Table 13). We therefore did not proceed with further regression analyses.

4. Discussion

The goal of this longitudinal project was to broaden understanding of the relations between early science-related input and children's emergent scientific literacy by building upon data first collected at 3 years of age and reported in Booth et al. (2020). In that initial analysis, the degree to which parents invited their children to explain causal phenomena, but not the degree to which

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TABLE 12 Multivariate regression analysis for home science environment at Waves 1 and 2 predicting scientific literacy (with StimQ).

Outcome	Predictor	Unstandardized		Standardized	*t*	*p*	95% CI		*sr*
		B	SE	β			*LL*	*UL*	
Wave 1									
SciLit2	Intercept	−1.01	0.75	−0.07	−1.33	0.18	−2.48	0.47	
	HomeSci1	0.03	0.02	0.09	1.08	0.28	−0.02	0.07	0.08
	Lens 1	0.50	0.09	0.51	5.58	<0.001	0.32	0.67	0.41
	NIH-ECB1	0.01	0.01	0.21	2.57	0.01	0.00	0.03	0.16
	StimQ1	0.02	0.02	0.08	0.83	0.41	−0.02	0.05	0.07
SciLit3	Intercept	−1.65	0.94	0.01	−1.75	0.08	−3.49	0.20	
	HomeSci1	0.06	0.03	0.22	2.05	0.04	0.00	0.11	0.18
	Lens1	0.38	0.10	0.33	3.90	<0.001	0.19	0.57	0.32
	NIH-ECB1	0.01	0.01	0.18	1.51	0.13	0.00	0.02	0.12
	StimQ1	−0.01	0.02	−0.02	−0.41	0.68	−0.05	0.03	−0.04
Wave 2									
SciLit3	Intercept	−2.08	0.86	0.06	−2.43	<0.001	−3.58	−0.40	
	HomeSci2	0.02	0.03	0.09	0.76	0.48	−0.03	0.07	0.07
	Lens2	0.52	0.11	0.51	4.97	<0.001	0.31	0.73	0.43
	NIH-ECB2	0.01	0.01	0.13	1.59	0.13	0.00	0.02	0.12
	StimQ1	−0.01	0.02	−0.01	−0.36	0.72	−0.04	0.03	−0.03
SciLit4	Intercept	−2.89	0.99	0.10	−2.93	<0.001	−4.51	−0.95	
	HomeSci2	0.05	0.03	0.20	1.76	0.05	0.00	0.11	0.18
	Lens2	0.47	0.14	0.40	3.38	<0.001	0.20	0.74	0.35
	NIH-ECB2	0.01	0.01	0.15	1.35	0.17	−0.01	0.03	0.12
	StimQ1	0.00	0.02	0.00	−0.02	0.99	−0.04	0.04	0.00
SciLit5	Intercept	−1.53	1.02	0.07	−1.75	0.13	−3.60	−0.47	
	HomeSci2	0.06	0.03	0.17	2.02	0.04	0.00	0.11	0.20
	Lens2	0.50	0.13	0.47	3.98	<0.001	0.24	0.75	0.41
	NIH-ECB2	0.01	0.01	0.12	1.05	0.43	−0.01	0.02	0.09
	StimQ1	−0.02	0.02	−0.14	−1.01	0.31	−0.07	0.02	−0.11

SciLit, Scientific Literacy at Wave 3, 4, and 5 is a standardized composite score but is a single score at Wave 1 and Wave 2; Lens, Lens on Science; HomeSci, Home Science Environment; NIH-ECB, NIH Toolbox Early Childhood Cognition Battery; StimQ, StimQ-Preschool; CI, confidence interval; LL, lower limit; UL, upper limit; sr = semi-partial (part) correlation. The number following the task abbreviation is the measurement wave.

TABLE 13 Bivariate correlations for home science experience and math and literacy achievement.

	Home science environment									
	Wave 1		Wave 2		Wave 3		Wave 4		Wave 5	
	Act	Mat	Act	Mat	Act	Mat	Act	Mat	Act	Mat
Math	0.13	0.03	0.08	0.05	−0.05	0.01	0.04	0.01	0.14	0.23
Literacy	0.28	0.18	0.05	0.13	0.07	0.13	0.07	0.17	−0.11	0.27

Act, Activity; Mat, Material; Math, TerraNova Math Subtest taken at Wave 5; Literacy, NIH Toolbox Oral Reading Recognition Test taken at Wave 5.

they provided causal explanations themselves, correlated with children's contemporaneous scientific literacy. Although it was only considered as a control variable in Booth et al. (2020), the home science environment also accounted for unique variance in children's scientific literacy. In the current work, we therefore considered further parent invitations of causal explanations, while also closely examining the broader home science literacy environment. Overall, our investigation revealed that exposure to science-related input plays a particularly powerful role in shaping scientific literacy when children are very young and just entering preschool. This broad conclusion holds when considering both parent causal-explanatory talk and exposure to science-related home environment, but the latter effects were substantially more robust and long-lasting.

With respect to parent causal-explanatory talk, we found that parent invitations to explain causal phenomena were related to children's scientific literacy concurrently and one year later. However, because this singular longitudinal association failed to hold when controlling for initial scientific literacy, no clearly predictive relations were evident. It is entirely possible that, if a predictive relation between parent invitations to explain and scientific literacy exists at all, it is confined to only the very earliest developmental window. Any correlations to later scientific literacy might well be due to subsequent stability in outcome measurements. Notably, no associations between the degree to which parents provided explanations themselves and children's concurrent or subsequent scientific literacy were observed at all. Although surprising given the theoretically plausible usefulness of these explanations for building scientific knowledge, this finding is consistent with results reported for the first wave of data collection in Booth et al. (2020). It is also consistent with evidence suggesting that explanations might actually curtail learning under some circumstances by undermining children's own exploration and discovery process (e.g., Bonawitz et al., 2011; Brockbank and Walker, 2022).

Together, these results suggest that parent causal-exploratory talk plays little role in shaping emergent scientific literacy. However, related research has found parent explanatory talk to be positively related to children's concurrent science-related exploration and learning (Fender and Crowley, 2007; Marcus et al., 2018; Willard et al., 2019). Studies also find young children's self-generated causal explanations to promote foundational scientific skills such as causal learning, and hypothesis generation, and revision (e.g., Walker et al., 2017; Busch et al., 2018).

Our failure to observe robust associations between aspects of parent causal talk and children's scientific literacy might be due to limitations of our measurement approach. First, our observations were quite brief and constrained to laboratory settings (with the exception of the one museum observation at 3 years). While the play materials available in these contexts were intended to evoke natural conversations about causality, other or more varied options might have been more successful. More extended recordings in the home would have perhaps been most ideal for capturing natural variation. Second, our coding of the existing data did not capture potentially important nuances in the input. For example, we did not consider the quality of explanations produced by parents or children. Studies find explanations produced by parent and children are not always accurate or exhaustive (Snow and Kurland, 1996; Kelemen, 1999; Crowley et al., 2001; Gelman, 2003), and it might be that quality is an important moderator of relations between parent talk and children's scientific literacy (Fender and Crowley, 2007; Mills et al., 2022). Parent invitations for children to explain might also be most likely to elicit responses when they are attuned to the child's level of knowledge and interests (Chouinard et al., 2007). Finally, given that the only hints of association between parent causal-explanatory talk and children's scientific literacy were evident at our earliest 3-year-old measurement, it is also possible that effects would have been stronger if we observed even earlier developmental windows.

In contrast to the relatively weak effects observed in consideration of parent causal-explanatory talk, our analyses of the broader home science environment were much more promising. Specifically, we found the home science environment at Wave 1 to be related to contemporaneous scientific literacy, as well as to scores at subsequent Waves 2 and 3. These longitudinal relations held even when controlling for initial scientific literacy scores and could not be fully accounted for by general cognitive abilities. Similarly, the home science environment measured at Wave 2 predicted concurrent scientific literacy, as well as scores at all subsequent measurement waves. These relations variably held when baseline scientific literacy and cognitive skills were included as controls. Importantly, reciprocal relations between early scientific literacy and later home science environment were rare and relatively weak, failing to maintain after controlling for baseline home science environment.

Interestingly, the most robust and longest lasting associations were observed in exploratory analyses differentiating home science activities from access to science-related materials. Indeed, home science activities, such as conducting experiments and visiting science museums, measured at 3 years as children were entering preschool, predicted scientific literacy through first grade. Home science materials, in contrast, failed to maintain any predictive power on their own (after controlling for baseline scientific literacy). One possibility is that materials are less important to emergent scientific literacy because children these young are unable to gain much from them of conceptual value through exploration on their own. Their value might therefore derive entirely from interactions they stimulate with parents, which would be subsumed by our measure of home science activities. It is also entirely possible that learning about the causal fundamentals of science at these early ages can be easily achieved with household items in the context of everyday activities like bathing and cooking, thus obviating the need for extensive collections of specifically science-themed materials.

Although nuanced, and in need of replication and further confirmation through intervention studies, the overall pattern of results is consistent with enduring effects of the home science environment on the subsequent development of children's scientific literacy. Moreover, this relation appears to be quite specific. Effects of science-related aspects of the home environment were generally stronger than those of cognitive stimulation more generally speaking, and some of the former maintained even when controlling for the latter. In addition, the home science environment differentially predicted scientific, in contrast to math or reading, literacy.

In sum, this project demonstrates that children's exposure to science related experiences as they enter preschool are predictive of their scientific literacy up to 4 years later. The fact that experiences at home appear to relatively decrease in importance as children spend more time in other contexts (e.g., preschool) is consistent with broad socio-ecological theories of development (e.g., Bronfenbrenner, 1986). Interestingly, a similar developmental pattern was observed for relations between children's causal stance (i.e., interest and attunement to causality) and subsequent scientific literacy in another arm of this longitudinal project (Booth et al., 2022). In contrast, however, longer-lasting reciprocal relations were observed between children's causal reasoning skills and developing scientific literacy (Shavlik et al., 2022). A better understanding of relations between these factors will be central to pinpointing the most impactful levers for addressing opportunity gaps and inequalities in science-related educational outcomes. Nevertheless, this study clearly converges on the importance of focusing on preschool, and potentially even earlier developmental windows as we proceed in these investigations.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: OSF (https://osf.io/z7cgd).

Ethics statement

The studies involving human participants were reviewed and approved by Institutional Review Board at Vanderbilt University, and Institutional Review Board at the University of Texas at Austin. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

AB and CH contributed to the design of the research. JB, MS, AB, and CH analysis of the results. JB, MS, CS, and AB wrote the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Promoting children's science, technology, engineering, and mathematics learning at home through tinkering and storytelling

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This study examined whether connecting storytelling and tinkering can advance early STEM (science, technology, engineering, and mathematics) learning opportunities for children. A total of 62 families with 4- to 10-year-old (M=8.03) children were observed via Zoom. They watched a video invitation to tinker at home prepared by museum educators prior to tinkering. Then, half of the families were prompted to think up a story before tinkering (story-based tinkering group), whereas the other half were simply asked to begin tinkering (no-story group). Once they had finished tinkering, researchers elicited children's reflections about their tinkering experience. A subset of the families (n=45) also reminisced about their tinkering experience several weeks later. The story instructions provided before tinkering engendered children's storytelling during tinkering and when reflecting on the experience. Children in the story-based tinkering group also talked the most about STEM both during tinkering, and subsequently when reminiscing with their parents about their tinkering experience.

KEYWORDS

storytelling, STEM learning, parent-child interactions, memory, informal learning, museums

Introduction

In this study, our goal is to understand how storytelling can be integrated into informal science, technology, engineering, and mathematics (STEM) learning experiences for children at home. Although most of the research and educational practices involving stories concern developing language and literacy skills, there is growing interest in and evidence for stories fostering children's STEM learning (see Haden et al., 2023, for review). This is important because it contributes to a broader effort in the United States to design and implement educational opportunities that can build competencies in STEM and support future STEM-related pursuits (National Research Council [NRC], 2012; NGSS Lead States, 2013). In addition to education in schools, informal learning experiences in homes, museums, and libraries can promote the development of skills and competencies that are important in STEM fields (National Academy of Engineering [NAE] and National Research Council [NRC], 2009; National Research Council [NRC], 2009, National Research Council [NRC], 2012; Sobel and Jipson, 2016; NAS, 2018). In terms of specific STEM-related activities, one that has been underscored by educators and policymakers is *tinkering*, a form of playful, hands-on problem solving involving everyday

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materials (Honey and Kanter, 2013; Bevan, 2017). Some argued that tinkering is a nearly ideal target for research and educational practices that aim to encourage STEM because of its "low floors" to get started, "high ceilings" that do not limit complexity of projects, and "wide walls" that can engage learners from many different backgrounds and interests (Resnick, 2016; Vossoughi et al., 2016; Acosta, 2022). However, to realize the potential for tinkering to foster children's STEM learning, we must expand the range of educational practices that engage children in STEM-rich tinkering (Pagano et al., 2020). This is a primary aim of our work in which we ask the research question of whether prompting parent–child oral storytelling while participating in tinkering at home can advance informal STEM learning opportunities for children.

Stories for promoting STEM learning

Children begin telling stories almost as soon as they begin talking, and stories in books, movies, videogames, and television shows, as well as oral stories in conversations with others are ubiquitous in the lives of children. A great deal of theory and research recommends stories for successful learning generally (e.g., Nelson, 1989; Bruner, 1996; Brown et al., 2014), as well as for science learning specifically (Avraamidou and Osborne, 2009; Frykman, 2009; Klassen, 2010; Dahlstrom, 2014; Browning and Hohenstein, 2015; Wilson-Lopez and Gregory, 2015). There is also growing emphasis on stories beyond books, including oral storytelling (Haden et al., 2023). This is in keeping with Bruner's (1991) theorizing that oral stories are a natural way of conveying knowledge that perhaps is more engaging for children and adults than STEM-related texts. Importantly, broadening the focus on stories to include oral storytelling may harness cultural resources for supporting children's STEM learning at home (Haden et al., 2023). For example, for families from Latin American heritage and other cultural communities with firmly rooted oral traditions, oral storytelling may be a more common everyday practice for conveying knowledge to young children than book reading (Sánchez, 2009; Melzi et al., 2019).

There are several reasons why stories can support rich opportunities for children's STEM learning. For one, stories can convey science information that may not be available through direct hands-on experiences with objects, and foster children's engagement with abstract and challenging STEM-related ideas (National Research Council [NRC], 2009; Kelemen et al., 2014; Browning and Hohenstein, 2015; Evans et al., 2016; Cho and Plummer, 2018). Additionally, stories follow a narrative structure that can add coherence to experiences and enhance understanding of causal relations (Bruner, 1991; Trabasso and Stein, 1997; Reese et al., 2011). In turn, more coherent representations of STEM information and experiences can support retention and transfer of STEM learning (Klassen, 2010; Dahlstrom, 2014). Stories can also ground hands-on STEM activities and abstract STEM-related concepts in meaningful, interesting, and accessible scenarios, and help children realize the utility and relevance of mathematical, scientific, and engineering concepts and problems in their everyday lives. Furthermore, drawing on sociocultural theories that emphasize social communicative exchanges between children and caregivers (e.g., Vygotsky, 1978; Rogoff et al., 2018), stories can promote elaborated conversations involving cognitively challenging language, scaffolding children's engagement with STEM-related principles and practices (Solis and Callanan, 2018; Plummer and Cho, 2020; Shirefley et al., 2020). Whereas children can learn a lot through direct experience interacting with objects (Piaget, 1970; Vygotsky, 1978), the kinds of conversation that stories can engender may provide critical supports for learning (Jant et al., 2014). In sum, stories can strengthen STEM learning by making what gets into memory more concrete, coherent, and comprehensible, thereby offering powerful mechanisms for children's STEM learning.

Evidence that stories can support STEM learning comes from work in schools and informal educational settings. For example, there are a number of early childhood curriculum and resources for teachers in schools that use stories to contextualize hands-on activities about mathematics, science, and engineering (e.g., Brophy et al., 2008; Casey et al., 2008; van den Heuvel-Panhuizen et al., 2009; Elia et al., 2010; Aguirre-Muñoz and Pantoya, 2016; Cunningham, 2018; English and Moore, 2018; Giamellaro and O'Connell, 2018; Stanford et al., 2021). For example, in the *Engineering is Elementary (EiE)* curriculum[1] (Cunningham and Lachapelle, 2014), a unit on bridge building is introduced with a story about a boy named Javier who lives in Texas and explores the field of civil engineering so as to build a stronger bridge to his backyard fort. *EiE* reports pre- to post-test gains in understanding of the engineering design process, and benefits for students' confidence and attitudes about future STEM-related education and careers choices (Cunningham, 2018). As another example, Casey et al. (2008) designed a series of block building activities that for one group of kindergarteners were paired with oral stories told by a teacher from a book. Children in the building + story condition, for instance, heard that Sneeze the dragon wanted a 2-blocks high wall around the castle grounds to help keep animals from jumping over. Children in the building only condition were invited to build an enclosure with the same constraints without the story context; those in the control condition participated in unstructured block building. Compared with children in build-only and control groups, those in the building + story condition showed the greatest pre- to post-test improvements in spatial skills that are positively associated with STEM abilities.

Our focus on stories and tinkering at home is further encouraged by work in informal educational settings (e.g., Luke et al., 2010; Murmann and Avraamidou, 2016; Pattison et al., 2022). Plummer and Cho (2020) designed story-driven science programs for preschoolers. For example, after reading *Moonbear's Shadow*, a museum educator prompted children to investigate the relations between a light source (flashlight), object (plastic bear toy), and shadows, which led the children to co-construct evidence-based explanations. In Letourneau et al. (2022), 7- to 14-year-old girls were observed during museum-based engineering design activities that used elements of stories (characters, settings, problems) to prompt consideration of who and what their designs were for. The stories supported engagement in multiple engineering design practices, expressions of empathy for the characters, and the making of connections between the stories and the girls' personal experiences. Tzou et al. (2019) invited Indigenous families to animate family oral stories using robotics and computer coding during library-based workshops. As families enacted their stories with the roboticized dioramas they created, the stories not only

1 www.eie.org

framed material exploration and design, but also motivated goals and fixes for story-related problems. Further, Solis et al. (2019) found that when library- and museum-based programs for families were led by engineering experts who told oral engineering stories to frame hands-on activities, families talked more about engineering when engaging in the activities. In turn, the children also reported more engineering information in their reflections about the activities immediately afterward.

Our consideration of stories that parents and children tell is based in prior work suggesting that if stories can engender STEM-rich conversations, STEM learning can result. The frequency of specific STEM-related language inputs, such as spatial and relational language and mathematical vocabulary, can predict children's skills in STEM domains (Gunderson and Levine, 2011; Pruden et al., 2011; Hassinger-Das et al., 2015; Casasola et al., 2020). Likewise, work on family conversations in museums, libraries, and at home suggests that the content of parent–child conversational interactions can support children's STEM learning (Crowley et al., 2001; Geerdts et al., 2015; Callanan et al., 2017; Eberbach and Crowley, 2017; Solis et al., 2019; Booth et al., 2020). For example, Willard et al. (2019) found that the more parents and children engaged in explanatory talk in a STEM-related museum exhibit the more children talked about causal mechanisms and engaged in STEM-related practices in the exhibit. Also, parent–child STEM talk during science and engineering activities in museum exhibits has been linked to children's recall of STEM-related information immediately after exhibit experiences, and in conversations and activities at home days and weeks later (Benjamin et al., 2010; Leichtman et al., 2017; Marcus et al., 2017; Pagano et al., 2020; Acosta et al., 2021; Marcus et al., 2021; Sobel et al., 2022).

The current study

In this study, we aimed to engage parents and children in storytelling during a tinkering activity that they participated in at home. Tinkering often involves everyday, familiar, and recyclable materials (e.g., cardboard, paper, glue, and tape)—things families have around their homes. Tinkering is also frequently social, involving multiple family members (Vossoughi and Bevan, 2014). Early STEM learning opportunities can be greatly enhanced when tinkering centers on participants' own ideas and objectives, as opposed to other sorts of building activities where there is a set or prescribed outcome (e.g., building a house with pieces and directions from a kit; Bevan, 2017). Moreover, tinkering can connect with STEM-related principles and practices in a range of ways (Vossoughi and Bevan, 2014; Pagano et al., 2020; Acosta et al., 2021). For example, tinkering creates opportunities for families to engage in the engineering design process, including making something to address a problem or need, and iterating the design after testing it for success (Cunningham and Lachapelle, 2014: Vossoughi et al., 2016). Math and science engagement is evident during tinkering as well, such as when children talk about how high some part of the structure needs to be, explain the relations between the parts and the whole of a structure, and discuss their thinking about what might work or not work in making and iterating their creation (Diefes-Dux, 2015).

For this study, as part of a research-practice partnership between university researchers and informal STEM learning practitioners at Chicago Children's Museum, educators created a videorecorded invitation for families to tinker at home. This was at the start of the COVID-19 pandemic when the museum temporarily closed to visitors. In the video, an educator invited families to tinker to make a playground ride for a toy friend using materials they had around their home, and encouraged engagement in storytelling and the engineering design process. In addition to the dissemination of the video invitation on the museum's website and social media platforms, our team began recruiting research participants. With half of the families in the research sample, we further encouraged telling stories during tinkering (i.e., story-based tinkering) by providing some time to think up their story before tinkering. During tinkering, we measured whether and to what extent families were telling stories by measuring the frequency of story talk, as well as the frequency of STEM-related talk during tinkering.

Immediately after tinkering we invited children's reflections about the tinkering experience. Reflection is both a crucial part of the learning process and a means for revealing learning outcomes (e.g., Marcus et al., 2021). Reflection is also foundational in modern STEM education (e.g., National Research Council [NRC], 2009; NGSS Lead States, 2013). Opportunities to reflect on hands-on activities shortly after they have taken place can support the process of consolidation, whereby ephemeral patterns of experience are strengthened and transformed into lasting memories (Pagano et al., 2019). It also seemed possible that children who engaged in story-based tinkering would engage in more story and STEM talk about their tinkering experience immediately afterward, potentially drawing on the story they had told, which might help organize their engagement in engineering design and other STEM-related practices and support their reports. Furthermore, we engaged children in reminiscing with their parents several weeks after the tinkering experience, following up with them again via Zoom. These reminiscing conversations offered a vantage point from which to assess what STEM-related information had been retained post-tinkering and whether those in the story-based tinkering group were better able to recall this information compared to the no-story group.

We tested several sets of hypotheses. First, we hypothesized that children and parents who were prompted to tell a story during tinkering would mention more story components and talk more about STEM during tinkering than those in the no-story condition. Secondly, we predicted that when compared to those in the no-story during tinkering condition, children in the story-based tinkering condition would talk more about story and STEM in their immediate reports after tinkering. Lastly, we hypothesized that children in the story-based tinkering condition would talk the most about STEM when reminiscing with their parents weeks after tinkering. Essentially, we expected that prompting storytelling during tinkering at home would support children's understanding and remembering of STEM information and that this would be evident both in their immediate reflections and later post-tinkering reminiscing.

Methods

Participants

Sixty-two families with 4- to 10-year-old children (M_{age} = 8.03, SD = 1.72; 30 girls) participated in this study. We elected to focus on this age group because research shows that the preschool and early elementary years can be a crucial period for advancing STEM learning and interest (National Research Council [NRC], 2012). Also, this is the age group that our partners see in the museum's Tinkering Lab exhibit, and the ages for whom they designed the online programming during the pandemic. Families were recruited with the help of Chicago Children's Museum's outreach efforts, by recontacting families previously observed at the museum in different studies, and through word of mouth. Based on parent report, 54.8% of the children were White, 14.5% Black, 8.1% Asian, 4.8% Latinx, and 16.1% mixed race/ethnicity (race/ethnicity information was missing for 1 child). Of the parents, 87% held a college degree or higher. Of the 57 families who reported family income, 14.5% earned $200,000 or more, 12.9% earned $150,000-199,999, 30.6% earned $100,000-149,999, 22.6% earned $75,000–$99,999, 9.7% earned $50,000-74,999, and 1.6% earned $25,000-49,999. Of the families, 56.5% participated in our previous studies.

Procedure

The study was approved under Loyola University Chicago IRB protocol #2992, *Tinkering with Digital Storytelling.* A researcher met with each family individually via Zoom for two sessions which were video- and audiorecorded. The first session involved observations of parents and children tinkering at home followed by a researcher eliciting the children's reflections. The second session was to record parent–child reminiscing conversations.

Observations of tinkering at home

Prior to the first Zoom meeting, parents gave consent and were provided with a list of suggested materials to collect in advance of our tinkering observation session. These materials included paper, cardboard, tape, string, and glue. At the outset of the first session, we spent a few moments with each family ensuring that the camera angle was such that we could observe the parents and children in the workspace they had selected in their homes to engage in the tinkering activity.

All parents and children watched via Zoom a 5-min video introduction to the tinkering activity. The video was created by educators at Chicago Children's Museum and introduced the tinkering at home activity: to create a playground ride for a small toy friend.[2] In the video, a museum educator introduced several steps to complete the tinkering activity, including choosing a small toy, planning, making the ride, and sharing a story about the toy and the ride. The video also described the engineering process of making, testing, and fixing the creation, and illustrated these practices with an example of a swing the educator made for her character "Crunch" (a cork with eyes drawn on it) from cardboard, rubber bands, sticks, string, and tape.

After participants viewed the video, the researcher explained to all families that they had 30 min to complete the tinkering activity. During tinkering, the researcher turned off their camera and microphone to avoid drawing attention to the videorecording. When the 30 min were up, all families were given the option of taking up to 5 more minutes to finish up.

Families were randomly assigned to either the story-based tinkering condition ($n = 29$) or the no-story tinkering condition ($n = 33$). Immediately after the video invitation to tinker concluded, the families in the no-story condition were invited to start tinkering. Those in the story-based tinkering condition were asked by the researcher to spend a few minutes thinking up their story about their toy friend and their playground ride, what the toy would ride on, and how they could make it fun and safe. Each of these elements had been mentioned in the video; the story-based tinkering condition was aimed at emphasizing the storytelling component of the activity, and to give families in this group time to develop their story before beginning tinkering. Once families in this condition said they were ready, they began the tinkering activity.

Children's reflections immediately after tinkering

Immediately after tinkering, researchers invited all children to show off their creations. The researcher then elicited all children's reflections about their tinkering experience through a series of questions: (1) Tell me all about what happened with your character today? Tell me all about what they were thinking and doing! (2) What did you make for your character? (3) How did you make it for them? (4) Did you test your project to see if it worked? (5) How did it turn out? (6) Did you have to change or fix anything? (7) What did you learn? Researchers followed up with "Tell me more" and other encouragement as the children provided their reports in response to the prompts. After the children's immediate reflections, the researcher asked the parents to report demographic information (including parent education, family income, and parents' occupation) and about children's prior experiences.

Parent–child reminiscing

A researcher who had not observed the families for the first session conducted the second session via Zoom. Our protocol was for the second session to occur approximately 2 weeks after the initial tinkering session. The researcher invited the parents and children to talk about the tinkering activity from the very beginning to the very end the way they would normally talk about past experiences together.

Coding

All coding was conducted based on video recordings and transcripts. For each coding system, two coders independently coded 20% of the data, scoring the parents' and children's talk separately, to establish interrater reliability.

Parents' and children's story talk

Development of the story coding scheme was informed by the work of Hickmann (2003) that emphasized the importance of maintaining and reintroducing characters as a crucial narrative skill that allows the children to chart the progress of characters and elaborate their roles as the plot progresses. We coded for the frequency of story talk, including questions or comments about *characters*—naming the toy friend or object representing the

2 https://www.youtube.com/watch?v=PRTwI9vDFoM

character the creation was being built for, describing personality characteristic (e.g., "She likes to ride fast."), desires (e.g., "He wants it to be yellow."), or talking for the toy; *settings*—naming locations or physical surroundings (e.g., "It's in a park." or "It's on a beach."), or mentioning imagined places (e.g., "It's in a magical forest."); *actions*—within the story such as descriptions of physical movements (e.g., "He climbed up the ladder.") or explanations of the plot (e.g., "He's waiting for his friend to come over."); and *conflicts/problems*—about obstacles or challenges that the toy is facing while on the playground ride, or problems that the toy must overcome (e.g., "She is too small to reach the button." or "Her hat keeps falling off."). Interrater reliability using Cohen's Kappa was 0.91 for parents' talk and 0.88 for children's talk during tinkering, and 0.92 for the children's story talk in the reflections immediately after tinkering.

Parents' and children's STEM talk

Using a system adapted from prior work (Haden et al., 2014), we coded for the frequency of parents' and children's STEM talk, including questions or statements pertaining to *project naming*—what they were planning to build (e.g., "What do you want to make?; "I want to make a slide."), *planning*—suggestions or ideas about what to use next, *modifying design*—about making adjustments and improvements to the design while constructing, such as discussing the stability, strength, or adding new elements (e.g., "You have to have a strong foundation around everything!" or "Let's put this in the middle to make it more stable."), *testing*—about trying out their design (e.g., "Do you want to try it on the slide?"; "I want to see if it moves."), *iterating/improving*—about how to fix something that wasn't working (e.g., "How can we fix this?" "I need to fix this seat."), and *mathematics*—such as length, size, weight, height, measurement, distance, geometric shapes, and numbers (e.g., "We need 2 pieces of that strong string."). Cohen's Kappa averaged 0.86 for parents' talk and 0.91 for children's talk during tinkering, 0.88 for the children's reports immediately after tinkering, and 0.82 and 0.81 for the parents and children, respectively when reminiscing.

Results

Preliminary analyses

Preliminary analyses examined whether children in the two conditions (story-based tinkering, no-story) were equivalent in terms of child age, gender, and prior experiences, as well as parents' education and whether they had a STEM-related job. As would be expected based on our random assignment of participants to groups, there were no age differences between the children in the story-based tinkering ($M = 7.86$, $SD = 1.71$) and the no-story conditions ($M = 8.18$, $SD = 1.74$), $F(1, 61) = 0.53$, $p = 0.469$, $\eta^2 = 0.01$, nor were there any gender differences, $\chi^2(1, N = 62) = 0.000$, $p = 0.99$, Cramer's V = 0.002. Likewise, children's prior experiences as assessed at the end of the tinkering session via parent report did not differ across groups (see Supplementary Table S1 in the Supplementary material), all $Fs \leq 3.14$, $ps \geq 0.082$, $\eta^2 s \leq 0.05$. We found no differences between conditions for parent education, $F(1, 59) = 0.04$, $p = 0.852$, $\eta^2 = 0.00$, and family income, $\chi^2(5, N = 57) = 4.70$, $p = 0.453$, Cramer's V = 0.287, $p = 0.453$. Parents' occupations were categorized as STEM (35.5%) or non-STEM (62.9%) according to the Occupational Information Network[3] and there were no differences between the two conditions with respect to parents' occupation, $\chi^2(1, N = 61) = 0.68$, $p = 0.411$, Cramer's V = 0.11, $p = 0.411$. Therefore, these preliminary analyses indicated it was not necessary to control for any of these demographic and prior experiences variables in our main analyses.

We also examined whether families were engaging longer in the tinkering or the reminiscing conversations as a function of condition and found no differences. Specifically, families spent an average of 26 min tinkering. Families in the story-based tinkering group ($M = 27.06$, $SD = 3.36$) and the no-story tinkering group ($M = 26.13$, $SD = 4.58$) were not different in time spent tinkering, $F(1, 61) = 0.63$, $p = 0.430$, $\eta^2 = 0.01$. Further, families spent on average 6 min reminiscing about their tinkering experiences. Families in the story-based tinkering group ($M = 6.18$, $SD = 4.14$) and no-story tinkering group ($M = 5.59$, $SD = 2.41$), were not different in time spent reminiscing, $F(1, 49) = 0.11$, $p = 0.745$, $\eta^2 = 0.00$. Given these results, we did not control for time spent in our main analyses.

Tinkering activity

We hypothesized that children and parents in the story-based tinkering group would mention more story components and talk more about STEM during tinkering than those in the no-story condition. To test our hypotheses, we conducted a series of one-way ANOVAs. As shown in Table 1, children in the story-based tinkering condition mentioned more story components than those in the no-story condition, $F(1, 61) = 10.73$, $p = 0.002$, $\eta^2 = 0.15$. Children in the story-based tinkering condition also talked more about STEM while tinkering than those in the no-story condition, $F(1, 61) = 12.29$, $p = 0.001$, $\eta^2 = 17$. However, in contrast to our hypotheses, parents in the two conditions did not differ in their talk about story components, $F(1, 61) = 1.81$, $p = 0.183$, $\eta^2 = 0.03$, or STEM, $F(1, 61) = 0.41$, $p = 0.523$, $\eta^2 = 0.01$. When we further examined correlations between parents' and children's talk, we found that their story talk was correlated, $r = 0.56$, $p < 0.001$, whereas parents' and children's STEM talk during tinkering was not, $r = 0.01$, $p = 0.94$.

Immediate reports

We hypothesized that in comparison to children in the no-story condition, those in the story-based tinkering condition would report more story components and STEM information to a researcher immediately after tinkering. As shown in the middle of Table 1, children in the story-based tinkering condition did mention more story components than those in the no-story group, $F(1, 61) = 21.20$, $p < 0.001$, $\eta^2 = 0.26$. However, there were no differences between the story and no-story conditions with regard

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TABLE 1 Comparison between families in the story-based and no-story tinkering conditions.

	Tinkering condition						
	Story-based		No-Story				
	M	SD	*M*	SD	*F*	*p*	η^2
Story talk during tinkering							
Parents' story talk	6.07	3.25	5.06	2.65	1.81	0.183	0.03
Children's story talk	8.48	4.30	5.00	4.07	10.73	0.002	0.15
STEM talk during tinkering							
Parents' STEM talk	12.83	3.70	13.39	3.23	0.41	0.523	0.01
Children's STEM talk	7.28	1.96	5.45	2.11	12.29	0.001	0.17
Children's talk immediately after tinkering							
Children's story talk	11.21	2.08	8.45	2.56	21.20	0.000	0.26
Children's STEM talk	10.24	3.75	10.64	2.56	0.24	0.626	0.00
STEM talk during reminiscing							
Parents' STEM talk	9.05	4.22	7.13	2.88	2.95	0.093	0.07
Children's STEM talk	6.38	2.56	3.08	1.59	26.65	0.000	0.39

to the children's STEM talk in their immediate reports, $F(1, 61) = 0.24$, $p = 0.626$, $\eta^2 = 0.00$. Additional correlational analyses revealed that neither parents' nor children's story or STEM talk during tinkering was related to children's STEM- or story-talk during the children's reflections, $rs \leq -0.22$, $ps \geq 0.083$.

Reminiscing conversation

Recall that all families were invited to reminisce about their tinkering experiences during a second Zoom session. Of the 62 families that participated in the tinkering activity, 45 (73%) engaged in the reminiscing session (21 story-based tinkering, 24 no-story). Five additional families engaged in reminiscing but after a substantially longer delay than the other families (range 150–190 days) and were excluded from the analyses. We found only two differences between families who did ($N = 45$) and did not ($N = 12$) participate in the reminiscing session. As shown in Supplementary Table S2 in the Supplementary material, for parents' STEM talk during tinkering and children's story talk in the immediate reflections, the frequencies of talk were higher for those who did not complete the reminiscing conversations compared to those who did.

We hypothesized that the effects of story-based tinkering would be observed in children's talk about STEM weeks afterward. Specifically, we expected that compared to those in the no-story during tinkering condition, children in the story-based tinkering condition would report more STEM information during parent–child reminiscing weeks after tinkering. On average, the reminiscing conversations occurred 16.33 days after tinkering (range 10–30 days), and we controlled for the delay between tinkering and reminiscing in these analyses. We found that children in the story-based tinkering condition talked significantly more about STEM when reminiscing than those in the no-story condition, $F(1, 44) = 23.65$, $p < 0.001$. $\eta^2 = 0.39$. For parents' STEM talk we found no differences by condition, $F(1, 44) = 2.95$, $p = 0.093$, $\eta^2 = 0.07$.

Finally, we conducted a series of exploratory analyses focusing on the linkages between children's and parents' talk during tinkering and children's recall of the tinkering experience. There were no significant associations between parents' and children's STEM talk while tinkering and parents' and children's STEM talk when reminiscing, $rs \leq 0.23$, $ps \geq 0.12$. Children's STEM talk in the reflections immediately after tinkering also did not correlate with their STEM talk when reminiscing, $r = -0.14$, $p = 0.357$. Children's story talk in the reflections immediately after tinkering was significantly related to children's STEM talk during reminiscing, $r = 0.34$, $p = 0.024$. Additionally, whereas parents' story talk during tinkering was also not related to children's STEM talk during reminiscing, $r = 0.07$, $p = 0.663$, children's talk about the story components during tinkering was significantly related to children's STEM talk during reminiscing, $r = 0.46$, $p = 0.002$. Therefore, the more story components children mentioned during tinkering, the more children talked about STEM during reminiscing.

Discussion

Summary of findings

Taken together, the results of this study provide support for the idea that connecting storytelling and tinkering activities can advance early STEM learning opportunities for children. Prompting families to tell a story during a tinkering activity at home influenced children's provision of story elements both during tinkering and in their immediate reports of the experience. Therefore, the simple instructions provided before tinkering inviting families to think up a story resulted in differences in storytelling during tinkering. What is more, children in the story-based tinkering group talked the most about STEM both during tinkering, and when reminiscing with their parents about their tinkering experience weeks later. The results add to a growing literature suggesting ways parents and educators can promote children's STEM talk during STEM-related experiences that improve children's subsequent retrieval and reporting of STEM information (e.g., Marcus et al., 2017; Pagano et al., 2020; Acosta et al., 2021; Marcus et al., 2021; Sobel et al., 2022).

Storytelling and informal STEM education

Our focus on oral storytelling during tinkering reflects an effort to consider the role stories can have in supporting academic skills beyond language and literacy (Haden et al., 2023). Although less often the focus of research, oral storytelling can be a crucial way that children gain knowledge at home. Families in both the story and no-story condition included some story elements in their talk during tinkering, which is not surprising when one considers that the video invitation all families viewed included elements of and encouragement to tell a story. Nonetheless, the instructions from the researcher encouraging families in the story-based tinkering condition to think up their story prior to tinkering were additionally effective. Children who heard the story-based instructions included more story elements in their talk during tinkering than those who did not. Moreover, children in the story-based tinkering condition also engaged in more STEM talk than those in the no-story condition. Essentially, by marrying their stories to the reason to tinker (to make a playground ride for a toy friend) children talked more about story and STEM. In this way, our work connects with other recent work suggesting that when individuals are encouraged to tell stories during STEM activities more STEM talk can result (Tzou et al., 2019; Letourneau et al., 2022).

Somewhat unexpectedly, parents did not engage in more story or STEM talk during the activity as a function of story condition. We speculate that regarding story, the brief period when parents and children in the story-based tinkering condition thought up their story might have provided sufficient scaffolding for the children to author their own tale during tinkering. Regarding STEM, parents in both groups engaged in substantial STEM talk, nearly twice that of children. The video that families viewed introducing the activity was aimed at engaging all families in processes of planning, making, testing, and fixing, among other STEM-related practices (e.g., predicting, explaining, comparing), which would have provided a basis for STEM talk across both groups. We saw parents in both groups including elements of STEM talk to support their children's tinkering, suggesting that the design of the video itself in highlighting the engineering design process encouraged family STEM talk during the home tinkering activity. In fact, this result is consistent with other work in museum settings, suggesting that introducing key STEM principles ahead of engagement in a STEM activity is linked to STEM talk during activities (e.g., Benjamin et al., 2010; Haden et al., 2014; Marcus et al., 2021). That parents in the two groups did not engage differently as a function of our experimental manipulation is in line with past work. There is evidence that when parents are explicitly instructed to use elaborative conversational techniques, for example, they do use them more frequently than uninstructed parents (e.g., Boland et al., 2003; Jant et al., 2014; Chandler-Campbell et al., 2020). But other work further shows that when specific conversational strategies are not called out, there are no differences in parents' talk as a function of the intervention (Benjamin et al., 2010; Marcus et al., 2017).

The connection between story talk and STEM talk during tinkering is illustrated in the following excerpts of conversations between parents and children in the story-based tinkering condition. In the first, they are building a hot air balloon. The child's character seems to be at the forefront of the design process, as they are the one making suggestions and modifications to the hot air balloon being built. In particular, the child's focus on their character is evident when they suggest adding a handle to the balloon, a re-design aimed at meeting a character's need.

> Mother: We need these materials to make it stronger. Okay, now we are attaching it to this part right [attaches balloon].
> Child: Do we want it like that? Or maybe we can move it down. [moves balloon down].
> Mother: Okay, so you feel this way. Now here let's add tape.
> Child: They [the character] need something like this [points to door below balloon]. I think that we should add a handle for it to come in.

Likewise, in the next example from another family in the story-based tinkering condition, the child's suggestion to separate the hot tub from the drying off space by using bricks, and modifying the design to be larger, comes as part of an effort to consider the character's experience and comfort:

> Child: For sure we need something to separate the hot tub.
> Mother: Separate the hot tub from?
> Child: The place where you dry off. Now I need bricks of …like these to make it big. Good?
> Mother: Good!

Relative to the no-story group, children in the story-based tinkering group also talked more about story, but not STEM, in their immediate reports. Talking about the story in connection with tinkering in these reports may have served a consolidation function, further cementing the link between the story and STEM. The following example of a child in the story-based tinkering group illustrates how the story characters motivated making and iteration of their design:

> Researcher: So, can you tell me about how you tested all these different projects to make sure they worked?
> Child: Sure. The swing was first try. And the problem for the see-saw is that the people, the ponies fell out and then the seats came off. So we used packaging tape for this one and we used um rubber bands for both of them. And the rubber bands are bonus to a seat belt. We got it on the second try. The problem with this was that Mary couldn't stand up so we had to keep this in the middle and works as a ladder.

The immediate reports revealed that children in both the story and no-story groups were able to report similar amounts of STEM information in the immediate reflections. The children were recalling quite a bit of STEM content about their tinkering experiences. It is likely that the researcher's questions eliciting the children's reflections provided support for reporting STEM-related information, benefiting both groups of children to the same extent immediately after tinkering.

When we considered the results of reminiscing conversations that occurred several weeks after tinkering, we did find the anticipated differences in children's reports of STEM information. Compared to those in the no-story group, children in the story-based tinkering group talked more about STEM when reminiscing with their parents weeks after their tinkering experience. Parents in the two groups did not differ in the story or STEM talk during reminiscing, pointing to the unique role that the story-based tinkering had on children's abilities to retrieve and report their experiences later. Other work has similarly found delayed effects of enriched informal tinkering and building experiences, such that differences in recall of STEM-related information are most evident weeks later (e.g., Benjamin et al., 2010; Marcus et al., 2021). Likewise, in this study, the connection between the story and the STEM information forged during the tinkering activity and immediately afterward benefited children's later recall of STEM. The following excerpt from a family in the story-based tinkering condition illustrates how the connection between story and STEM during tinkering was further manifest in their subsequent remembering of the experience:

Child: We used the cups.
Mother: Oh yeah! We cut the cups.
Child: We kinda…
Mother: Because it think it was three cups, wasn't it?
Child: And then the other part that was taped came off.
Mother: Oh yeah.
Child: Then we used it as a door.
Mother: Oh yeah, that's right.
Child: I think that was really cool.
Mother: And how did they get to the slide? How did they get up there?
Child: They used the steps (laughs) that you built. They have to have like enormous feet or have really long legs.
Mother: So that didn't work that well did it.
Child: They had to jump up the stairs. Bounce down.
Mother: …And the slide was good, right? It worked.
Child: Mmhmm.
Mother: And they were contained at the bottom, right?
Child: Yeah. And then they could open the door. Otherwise, they'd be just trapped in there. A pile of unicorns.

Limitations, implications, and future directions

It is important to consider a range of ways that children engage with stories when thinking about how stories can support informal STEM learning. Stories are infused into many of the kinds of activities that children engage in at home, from videogames and television viewing, to book reading. But the scant attention to oral storytelling may limit insights into the ways that stories as everyday practices can provide mechanisms for children's STEM learning, especially for children from cultural backgrounds with rich oral traditions (Haden et al., 2023). One contribution of our work to educational practice is in showing how oral storytelling can increase STEM learning opportunities based in hands-on activities at home. Unfortunately, a limitation of our online work during the COVID-19 pandemic is that our recruitment strategy did not yield a diverse sample in terms of cultural background, socioeconomic status, or parental education. We have addressed this limitation, in part, in other work that focuses on Latine families' oral storytelling and tinkering at home (e.g., Acosta, 2022). Gaining understanding of how families from different cultural communities might benefit from online museum programming is important when we think about its potential to increase access and opportunities for STEM learning for all families, including those who, for various reasons, are not regular museum visitors.

It is encouraging that the video invitation to tinker at home was itself effective in engaging families in storytelling and STEM talk. We know from prior work that the mix of parent–child STEM-related talk observed during tinkering depends on the design of the tinkering activity (Pagano et al., 2020). The video invitation in this study emphasized the engineering design process, as well as mathematics (measuring) and science (explanations), and this emphasis was reflected in the conversations we observed. With the transition back to the museum, we have been considering with our museum partners how what was learned from the digital program can inform museum practice. Families do not usually view a video before engaging in tinkering in an exhibit space. Likewise, the facilitation provided by museum educators in tinkering exhibits is often briefer in introducing the activity, and sometimes turns intermittent as families progress through the activity. Families in exhibits are faced with a mix of familiar and potentially unfamiliar materials. There are also other families and models throughout the space that families might use to gain further information about what there is to do and learn. Due to these differences and others, it is crucial to take steps to study whether the current findings translate across settings, specifically from home to the museum. With the Chicago Children's Museum having reopened, we are engaging in this work now. From the current study, a further implication for practice is that connecting stories and hands-on activities from the outset of the activity can increase the opportunities for STEM learning these activities provide.

Additionally, our work encourages practices that invite reflection on STEM learning to advance and reveal learning. Moreover, the current findings regarding children's retention of STEM information support further consideration of whether STEM learning promoted by oral storytelling *transfers* across settings—for example, from home to museum, and museum to home. Past work does suggest that STEM learning at home is related to STEM learning in school settings (e.g., Skwarchuk et al., 2014; Junge et al., 2021; Westerberg et al., 2022). Less is known about how learning in museums transfers beyond museum walls, but the work that does exist (e.g., Marcus et al., 2017, 2021) recommends this is a promising avenue for future work. The findings from this study indicate that storytelling during STEM activities may be especially important in promoting such transfer, as evidenced by the fact that pairing storytelling and tinkering led to more durable and retrievable memories for the STEM learning experiences.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Loyola University Chicago. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

CH secured funding and with GS conceptualized the idea for this study. GS was responsible for the data collection and conducted the coding with SS. MM conducted the statistical analyses. CH, MM, and GS contributed to the writing. All authors read, edited, and approved the submitted version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1146063/full#supplementary-material

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Developing and validating a measure of parental knowledge about early math development

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Parents' knowledge about the math skills that most preschool-aged children can develop might be an important component of the Home Math Environment (HME) as it might shape their math beliefs and efforts to support their preschoolers' math development. This study aimed to systematically develop measures of parents' knowledge about two critical early math topics, numeracy, and patterning, across five studies conducted with a total of 616 U.S. parents of 3- to 5-year-olds (66% mothers, 54% sons, 73% White, 60% college-educated). Parents were recruited via CloudResearch or a university database. Study 1 focused on item generation to revise a previous measure to capture a wider set of children's early math skills and analysis of the psychometric properties of the measure after it was completed by 161 parents via a survey. Study 2 included an analysis of a new sample of parents (n=21) who responded to the measures twice across two weeks to explore test–retest reliability. The measures were iteratively revised, administered to new samples, and analyzed in Studies 3 (n=45), 4 (n=46), and 5 (n=344). The measures demonstrated adequate internal consistency and validity (construct, convergent, and discriminant) in Study 5 such as being positively related to parents' numeracy and patterning beliefs about their children. Overall, the newly developed measures satisfy standards for the development of an adequate measure and can be used to better understand what parents know about early math development and how this relates to the HME that they facilitate.

KEYWORDS

home math environment, early math development, patterning knowledge, parent math support, preschool skills, home numeracy development, knowledge of child development

Developing a measure of parental knowledge about early math development

The math support that parents provide their young children at home is predictive of their children's later math skills (Mutaf-Yıldız et al., 2020). There is wide variability in how often and in what ways parents provide early math support (e.g., Ramani et al., 2015; Susperreguy and Davis-Kean, 2016; Thippana et al., 2020). The expectancy-value theory (EVT) posits that parents' beliefs affect the academic supports they provide to their children which in turn influence their children's academic knowledge (Eccles et al., 1983; Jacobs et al., 2004; Eccles and Wigfield, 2020). Additionally, parents' knowledge about infant development has been theorized to shape their beliefs about and support for their children's development, including the home literacy environment that they facilitate (Bornstein et al., 2010; Sonnenschein and Sun, 2017). However, while EVT has been extended to include preschool children and the parental math beliefs and support which are relevant for this age group (e.g., Skwarchuk et al., 2014; Douglas et al., 2021), little research on parental math support has focused on parental knowledge about math development. We argue that parents' knowledge about early math development will help

TABLE 1 Demographic statistics of participants by study.

Variable	Frequencies (%)				
	Study 1 (*N*=161)	Study 2 (*N*=21)	Study 3 (*N*=45)	Study 4 (*N*=45)	Study 5 (*N*=344)
Mothers	52	86	67	71	56
Primary Caregiver	–	–	87	89	94
Child Age					
3-year-olds	30	–	35	31	52
4-year-olds	34	100	63	69	48
5-year-olds	36	–	–	–	–
Sons	55	57	49	47	61
Income					
Less than $45,000	–	5	29	31	28
$45,000 - $89,999	–	19	42	42	41
More than $90,000	–	76	29	27	32
Education					
Less than a Bachelor's	34	–	44	56	21
Bachelor's Degree	45	43	31	31	55
More than a Bachelor's	21	57	24	13	24
Race/Ethnicity					
White	75	76	67	69	77
Black	12	11	11	11	8
Asian or Pacific Islander	8	5	4	7	5
Biracial or Mixed Race	4	8	16	7	4
American Indian or Native or Other Race	1	–	–	6	6

explain variability in their math beliefs and support and be an important addition to theories of parents' early math support. Indeed, one study has found that among U.S. parents from low- and middle-socioeconomic (SES) backgrounds, parents' knowledge about early math development was a unique, positive predictor of their children's math skills (DeFlorio and Beliakoff, 2015).

A few studies have examined the nature of parents' knowledge about early math development. In one study, most UK mothers of 3- and 4-year-old children misunderstood the nuances of children's development of an early math skill (Fluck et al., 2005). In particular, most incorrectly anticipated that their child understood aspects of cardinality irrespective of their child's age and counting abilities. In another study, Canadian parents of 3- to 5-year-olds rated almost all activities on a provided list, including distractor activities like large muscle play, as being "Important" through "Essential" in promoting mathematical development (Skwarchuk, 2009). In the third study, parents from middle SES backgrounds had more accurate knowledge of which math skills were within the developmental range for typical 5-year-olds compared to parents from low SES backgrounds (DeFlorio and Beliakoff, 2015). Notably, parents' knowledge about early math development was measured in different ways across the three studies and the psychometric properties of the measures were not reported. Further, no study has examined parents' knowledge about early patterning development, an important component of children's math development (e.g., Sarama and Clements, 2004; Fyfe et al., 2019). Given the potential role of parents' knowledge about early numeracy and patterning development for the home math support that they provide, reliable and valid measures of their knowledge are needed. The current study aimed to validate a measure of parents' knowledge about early math development.

General method

A closed-ended, self-report measure of parents' knowledge about early math development was iteratively revised and administered electronically to 616 U.S. parents of 3- to 5-year-olds across five studies in 2021 and 2022. Parents were recruited via CloudResearch for each study except for study 2 in which parents were recruited via a university department database. For each study, parents were paid $1.80 to $10 for participating. Participant demographics and descriptive statistics for each study are reported in Tables 1, 2 respectively.

Study 1

Study 1 aimed to (1) develop a more comprehensive measure of parents' knowledge about early math development through item generation and (2) examine the refined measure's internal consistency and content and construct validity. The measure was administered to 161 parents of 3- to 5-year-old children via a survey after being revised. Parents also completed a survey about their math and literacy beliefs.

TABLE 2 Descriptive statistics of knowledge measure subscales across studies (average accuracy and standard deviations).

Measure	Study 1	Study 2		Study 3	Study 4	Study 5
		Time 1	Time 2			
Across all items	0.75 (0.12)	0.77 (0.10)	0.80 (0.10)	0.78 (0.07)	0.79 (0.08)	0.68 (0.12)
Numeracy	0.74 (0.17)	0.78 (0.13)	0.81 (0.15)	0.76 (0.14)	0.78 (0.13)	0.65 (0.17)
Within	0.82 (0.22)	0.88 (0.17)	0.85 (0.20)	0.85 (0.16)	0.80 (0.19)	0.79 (0.23)
Beyond	0.55 (0.39)	0.54 (0.40)	0.71 (0.34)	0.56 (0.38)	0.72 (0.35)	0.38 (0.37)
Pattern	0.76 (0.16)	0.79 (0.14)	0.82 (0.18)	0.80 (0.12)	0.81 (0.13)	0.68 (0.17)
Within	0.78 (0.20)	0.81 (0.20)	0.84 (0.27)	0.80 (0.18)	0.80 (0.18)	0.74 (0.24)
Beyond	0.70 (0.35)	0.78 (0.29)	0.78 (0.30)	0.81 (0.29)	0.84 (0.29)	0.54 (0.41)

[a]Study 4 and 5 included two additional patterning within items. [b]Study 5's mean excludes two items: numeracy within item 5 and pattern within item 10.

Beliefs about child math and literacy abilities

The parental beliefs survey was composed of items adapted from a previous instrument (Zippert and Rittle-Johnson, 2020). Specifically, they were asked, "How good is your child currently in each area listed below?." They reported about two numeracy items (i.e., "Counting and naming numbers" and "Comparing the magnitudes (size) of numbers"), two patterning items (i.e., "Noticing and making patterns" and "Figuring out what should come next in patterns"), and one literacy item "Learning to read and write." Their ratings of the two numeracy and two patterning items were averaged as measures of their perception of their child's numeracy and patterning abilities, respectively.

Knowledge about early math development survey

The measure was adapted from a previously used measure (DeFlorio and Beliakoff, 2015) whose instruction was "These following questions concern children's mathematical development during the preschool years. Which of the following abilities or skills do you believe typical children have developed before their 5th birthday?." The previously used measure had a dichotomous scale and used 23 items. It included 13 items on numeracy skills, with six items on skills that are within the typical developmental range for most five-year-olds and seven that are beyond their typical developmental range. The previous measure also included two items on patterning skills (both within the developmental range) and eight items on spatial skills (four within and four beyond).

Item generation and content validity

We discuss how we generated or revised items for the measure and how the items relate to the literature on early math development as evidence of the measure's content validity (Joint Committee on the Standards for Educational and Psychological Testing, 2014). Our goal was to have reliable subscales of early math domains, given previous research indicating that preschoolers can and should be learning about early math skills including patterning and spatial skills (Verdine et al., 2014; Fyfe et al., 2019). Thus, we created items to measure a wider variety of early math skills given that more than half of the items in the original measure focused on numeracy. For example, we created a new item, "Fill in the missing part of a pattern made of repeating objects (for example, circle, square, square, circle, square, ______, circle, square, square)" based on Rittle-Johnson et al. (2020) in order to include more items on patterning skills. In general, we referenced prior research on early math development to identify math tasks most children in the U.S. are able to accomplish independently before kindergarten or their fifth birthday (e.g., National Research Council, 2009; Claessens and Engel, 2013; Clements and Sarama, 2014; Rittle-Johnson et al., 2017, 2019; Litkowski et al., 2020a; Kaufman et al., 2021). See Supplementary Table S1 for details about the final measure's items including the origin of each item.

Overall, sixteen items (8 patterning, 5 numeracy, and 3 spatial) were inductively added to measure a wider variety of math skills and to make the measure similar across subscales. Nine items were dropped primarily because they were ambiguous or were very similar to other items (e.g., "Use a computer with age-appropriate software to learn math concepts" did not focus on a specific numeracy, patterning, or spatial skill). Ten items from the original measure were also revised for clarity. The instruction was also expanded with the addition of a sentence that reads "Please select 'yes' for each skill that you think most children in the United States correctly master by age five. Please select 'no' for each skill that you do not think most children in the United States correctly master by age five."

After the first round of edits, the measure included 30 items (10 numeracy, 10 patterning, and 10 spatial). Within each subscale, there were seven items on skills children typically develop by age five (within the developmental range) and three on skills children typically do not develop by age five (beyond the developmental range). Parents' correct responses to each item were scored as a 1 and incorrect answers were scored as a 0. Parents' scores were averaged to create a measure of their knowledge across numeracy, patterning, and spatial. Parents' scores were also averaged to create separate composite measures for numeracy, patterning, and spatial for their knowledge (1) across all items, (2) about skills within the typical developmental range for most preschoolers, and (3) about skills beyond the typical developmental range for most preschoolers.

Results

Reliability

We used Cronbach's alpha as an indicator of internal consistency and interpreted alpha levels based on previous research (Cooper and

Schindler, 2003; Cohen et al., 2007). The measure had moderate/acceptable internal consistency across all items ($\alpha = 0.60$) but had unacceptable reliability when considering subscales composed of all numeracy ($\alpha = 0.36$), patterning ($\alpha = 0.32$), and spatial ($\alpha = -0.02$) items. When considering only the items that are within the typical development range for preschoolers, the numeracy subscale had moderate/acceptable reliability ($\alpha = 0.69$), the patterning subscale had low reliability ($\alpha = 0.53$) and the spatial subscale had unacceptable (but much better) reliability ($\alpha = 0.45$). When considering the items that are beyond the typical development range for preschoolers, both the numeracy subscale ($\alpha = 0.69$) and patterning subscales ($\alpha = 0.67$) had moderate/acceptable reliability while the spatial subscale had unacceptable reliability ($\alpha = 0.46$). Given the poor reliability of the spatial subscales, we focused further analyses and revisions on the numeracy and patterning subscales.

Construct validity

We used Confirmatory Factor Analyses (CFA) to examine whether each subscale's items measured a shared construct as indicated by each item having a significant factor loading. All numeracy items loaded significantly onto a model with two correlated factors, with one factor including items that measure skills that are beyond the typical developmental range for preschoolers and the other factor including items that measure skills that are within the developmental range (see standardized factor loadings in Table 3). All patterning items except for item 5 ("Sort a set of objects into 3 groups based on color such as red, blue, and green") loaded significantly onto a similar 2-factor model (see standardized factor loadings in Table 4). Thus, we concluded that we have evidence of construct validity: all numeracy items do measure the same construct and most patterning items do measure the same construct.

We also compared the 2-factor models to 1-factor models which did not consider items measuring skills that are within the typical developmental range separately from items that measure skills that are beyond the typical developmental range. We found that the 2-factor model fit the data significantly better than a 1-factor model for both numeracy, $\chi^2(3) = 98.28$, $p < 0.001$, and patterning, $\chi^2(3) = 31.7$, $p < 0.001$. This finding suggests that the subscales (within the typical developmental range for preschoolers and beyond the typical developmental range for preschoolers) were unique. The subscales (within the typical developmental range for preschoolers and beyond the typical developmental range for preschoolers) were negatively correlated providing additional evidence that they were unique and needed to be treated as separate measures, $r_{\text{numeracy}}(159) = -0.25$, $p < 0.001$ and $r_{\text{pattern}}(159) = -0.33$, $p < 0.001$. Further studies focused on revising and validating the subscales consisting of items that are within the developmental range for most typically developing preschool-aged children given that the intended audience of the measure was parents of preschoolers. Additionally, the subsequent studies focused on validating the subscales among parents of 3-year-olds and/or 4-year-olds since the measures ask about skills that are relevant to preschool-aged children who are younger than 5 years old.

Study 2

Study 2 aimed to examine the internal consistency as well as test–retest reliability of the measures of parents' knowledge about early numeracy and patterning development with a new sample. The items were identical to Study 1, however, the question stem was revised to ask about "most children" instead of "typical children." The measure was administered twice across two weeks to 21 parents of

TABLE 3 Descriptive statistics for measure of parents' knowledge about early numeracy development within the developmental range.

Item	Study 1 (*N*=161)		Study 2 (*N*=21)	Study 3 (*N*=45)	Study 4 (*N*=45)	Study 5 (*N*=344)	
	M (SD)	Factor Loading[a]	*M* (SD)	*M* (SD)	*M* (SD)	*M* (SD)	Factor Loading[a]
Count a row of 15 objects (for example, count 15 plastic worms) [a]	0.96 (0.19)	0.29	0.89 (0.31)	1.00 (0)	0.93 (0.25)	0.94 (0.23)	–
Counts out the correct number of things when asked for a specific number of things up to 10 (for example gives 6 cookies when asked for 6 cookies)	0.81 (0.39)	0.68	92 (0.28)	0.93 (0.25)	0.91 (0.28)	0.89 (0.32)	0.39
Name the written numbers from 1 to 10 (for example, points to the 9 when asked "where is the number nine?")	0.87 (0.34)	0.48	97 (0.16)	0.89 (0.32)	0.87 (0.34)	0.86 (0.35)	0.50
Solve small addition or subtraction problems presented with objects (for example, 3 blocks and 2 blocks is ___ blocks)	0.73 (0.45)	0.51	84 (0.37)	0.73 (0.45)	0.76 (0.43)	0.82 (0.39)	0.30
Tell which of two spoken numbers between one and ten is bigger (for example, says "five" in response to "Which is bigger, five or two?")	0.86 (0.34)	0.51	92 (0.28)	0.93 (0.25)	0.78 (0.42)	0.76 (0.43)	0.58
Tell which of two written numbers between one and ten is bigger (for example, points to the written number 9 when shown the written numbers 2 and 9 and asked "Which is bigger")	0.86 (0.34)	0.52	89 (0.31)	0.84 (0.37)	0.72 (0.46)	0.76 (0.43)	0.54
Answer questions by adding or subtracting small numbers (for example, says "three" in response to "If you have four stickers and then you give me one of your stickers, how many stickers would you have left?")	0.65 (0.48)	0.44	70 (0.46)	0.60 (0.50)	0.63 (0.49)	0.68 (0.47)	0.35

[a]Factor loadings are standardized.

TABLE 4 Descriptive statistics for measure of parents' knowledge about early numeracy development within the developmental range.

Item	Study 1 (*N*=161)		Study 2 (*N*=21)	Study 3 (*N*=45)	Study 4 (*N*=45)	Study 5 (*N*=344)	
	M (SD)	Factor Loading	*M* (SD)	*M* (SD)	*M* (SD)	*M* (SD)	Factor Loading[a]
Continue a pattern of cubes (for example, blue, blue, red, red, blue, blue, red, red, __, __, __, _)	0.83 (0.31)	0.56	0.81 (0.40)	0.76 (0.43)	0.80 (0.40)	0.76 (0.43)	0.42
Use colored beads to make a simple pattern, such as a "blue-purple" pattern	0.88 (0.32)	0.37	0.92 (0.28)	0.91 (0.29)	0.85 (0.36)	0.78 (0.42)	0.34
Figure out what should come next in a simple pattern (for example: clap, stomp, clap, stomp, _, _)	0.85 (0.36)	0.34	0.84 (0.37)	0.98 (0.15)	0.87 (0.34)	0.72 (0.45)	0.45
Sort a set of objects into 2 groups based on color such as red and blue	0.91 (0.29)	0.19	1.00 (0)	1.00 (0)	93 (0.25)	91 (0.29)	–
Identify two patterns that follow the same rule made with different materials (for example, a block-block-ball pattern and a sun-sun-moon pattern are similar)	0.65 (0.48)	0.29	0.58 (0.50)	0.56 (0.50)	0.54 (0.50)	0.60 (0.49)	0.45
Fill in the missing part of a pattern made of repeating objects (for example: circle, square, square, circle, square, __, circle, square, square)	0.76 (0.43)	0.66	86 (0.35)	0.71 (0.46)	0.67 (0.47)	0.63 (0.48)	0.61
Make the same kind of simple pattern in their bracelet as their friends' bracelet, but using different colors (for example, your child makes a yellow-green pattern to match a friend's red-blue pattern)	0.60 (0.49)	0.24	0.69 (0.47)	0.67 (0.48)	0.78 (0.42)	0.65 (0.48)	0.38
Makes a repeating pattern (for example, makes a clap, spin, snap, clap, spin, snap pattern)	NA	NA	NA	NA	0.85 (0.36)	0.74 (0.44)	0.50
Copy a pattern someone else makes in the same way (for example, your child beats a drum in a loud-soft pattern just like do)	NA	NA	NA	NA	0.89 (0.31)	0.80 (0.40)	0.33

[a]Factor loadings are standardized.

4-year-old children. Parents were randomly assigned to a condition and received information about early numeracy or patterning skills between the sessions; however, analyzing the effect of this information is beyond the scope of this report. Additionally, to examine the clarity of the measure, a subset of parents ($n = 7$) completed a video-recorded think-aloud (van Someren et al., 1994) as they completed the measures. Specifically, they were told, "We want to understand how parents approach answering our questions. Please read the following questions aloud and think aloud while you decide which answer you will choose. Keep talking as you answer all the questions and try to say everything that goes through your mind."

Results

Reliability

In contrast to study 1, and perhaps due to the much smaller sample size, the measure's internal consistency was low for the items measuring numeracy skills within the typical developmental range for preschoolers ($\alpha = 0.53$) and moderate for the items measuring patterning skills within the typical developmental range ($\alpha = 0.64$) at Time 1. Notably, both subscales had high reliability at Time 2 after parents received some information designed to change their knowledge about early numeracy or patterning development ($\alpha_{numeracy} = 0.72$ and $\alpha_{patterning} = 0.87$). Additionally, these subscales had high test–retest reliability, with strong correlations between the numeracy scores, $r(19) = 0.65$, $p = 0.001$, and patterning scores, $r(19) = 0.80$, $p < 0.001$, across two weeks.

Think aloud

Two authors made notes about parents' comments and questions during the think-aloud sessions and identified themes that emerged among parents after discussing their notes. First, several parents posed clarifying questions to the experimenter as they participated in the think-aloud. Overall, parents asked nine questions as they read and responded to the knowledge measure. This included questions about the difference between "numerals" and "numbers" which suggested that some items' phrasing needed to be clarified as well as uncertainty about what was meant by "most children" in the knowledge measure question. We revised the measure based on this feedback. Second, many parents expressed being unsure about their answers to knowledge measure items. Parents frequently said "I do not know" (25 times) or "probably" (10 times) when thinking through their answers to individual items. This finding suggests that parents have little confidence in their knowledge about early math skills.

Studies 3 and 4

Studies 3 and 4 aimed to revise the measure based on the previous two rounds of data collection and examine the internal consistency of the revised measure. As such, the revised measure was administered to two new samples each including 45 parents.

Knowledge measure revisions

We examined item-total correlations, standardized factor loadings, and means and standard deviations of each item in Studies 1 and 2 to identify items that needed to be revised. Specifically, we flagged and revised items with item-total correlations less than 0.2 and non-significant factor loadings and items that over 95% of parents responded to correctly or incorrectly. One numeracy item was revised to increase its difficulty (from counting 10 objects to counting 15 objects) given that it was previously flagged twice for evidence of a ceiling effect (M = 0.96, SD = 0.19 in Study 1 and M = 0.89, SD = 0.31 in Study 2). Two patterning items about skills within the developmental range were added in case any patterning items needed to be dropped in further analyses given that five patterning items were flagged at least once for item-total correlations less than 0.2, nonsignificant factor loadings, and ceiling effect. The new version of the measure included 32 items.

Based on parents' questions during Study 2's think-aloud, we made changes to the phrasing of 13 items. For example, we changed "numerals" to "written numerals," added "spoken" at the beginning of phrases about "numbers" referencing numbers heard aloud, and removed "alternating" from the phrase "simple alternating pattern." We also modified the instruction to "Please select "Yes" for each skill that you think over 50% of children in the United States can correctly do by their 5th birthday. Otherwise, select "No."" This decision to specify "over 50%" was made based on some parents' comments that they were unsure what "most children" meant in study 2. Fifty percent has been used as a cutoff in previous literature to indicate proficiency levels (Claessens and Engel, 2013; Litkowski et al., 2020b).

Following Study 3, five numeracy and four patterning items were revised. The revisions included changes to wording to increase the clarity of seven items as well as to increase the difficulty of 2 items (e.g., "name the numerals from 1 to 5" was changed to "name the written numbers from 1 to 10").

Results

When considering the items that are within the typical development range for preschoolers, both the numeracy subscale ($\alpha = 0.45$) and patterning subscale ($\alpha = 0.49$) had unacceptable reliability in Study 3. The numeracy subscale continued to have unacceptable reliability in Study 4 ($\alpha = 0.44$), but the patterning subscale's scale reliability improved slightly ($\alpha = 0.52$).

Study 5

Study 5 aimed to analyze the knowledge measure with a larger sample using a pre-registered analytic plan.[1] Notably, the larger sample allowed for analyses like Confirmatory Factor Analyses. A secondary aim of study 5 was to understand how parents approached the measure and potential sources of their knowledge about early math development. As such immediately after the knowledge measure items, parents were asked to type a response to the question "Overall, how did you decide which answers to choose when deciding which academic skills most children in the United States develop by age five?"

Results

Reliability

Items focused on numeracy skills that are within the developmental range had low (but not unacceptable) reliability ($\alpha = 0.59$). The Kuder–Richardson Formula 20 (KR20), often considered a better measure of reliability for tests with dichotomous variables, yielded a similar estimate (0.60). One item ("Count a row of 15 objects") had a low item-total correlation. As such, it was excluded from further analyses. The patterning items that are within the developmental range had moderate/acceptable reliability ($\alpha = 0.65$ and KR20 = 0.66). As with patterning, one item ("Sort a set of objects into 3 groups based on color such as red, blue, and green") had a low item-total correlation and was excluded from further analyses.

Construct validity

We used CFA to examine whether each subscale's items measured a shared construct as indicated by each item having a significant factor loading (see standardized factor loadings in Tables 3, 4). All numeracy items measuring skills within the typical developmental range for most preschoolers loaded significantly onto a factor. Similar to study 2, all patterning items measuring skills within the typical developmental range except for item 5 loaded significantly onto a factor. Importantly, the models fit the data well according to several indices such as a nonsignificant chi-square, Comparative Fit Index >0.9, Root Mean Square Error of Approximation <0.08, and Adjusted Goodness of Fit >0.9 (see Supplementary Table S2). Thus, we concluded that after dropping item 5, we have evidence of construct validity: numeracy items do measure the same construct and patterning items do measure the same construct.

Convergent validity

Next, we measured the convergent validity of the numeracy and patterning subscales. The Joint Committee on the Standards for Educational and Psychological Testing (2014, p. 16–17) reports that "relationships between test scores and other [external] measures intended to assess the same or similar constructs provide convergent evidence." We view parents' knowledge and beliefs as similar constructs-two types of parental cognitions that potentially influence their support. We examined whether parents' knowledge about numeracy skills that most children develop by age 5 was related to their beliefs about their child's numeracy ability and did the same for patterning. We found evidence of convergent validity for both. Specifically, parents' knowledge about early patterning development was significantly correlated with their perception of their child's patterning abilities, $r(342) = 0.24$, $p < 0.001$. Parents' knowledge about early numeracy development was also significantly correlated with their perception of their child's numeracy abilities, $r(342) = 0.11$, $p = 0.036$.

Discriminant validity

In line with research indicating that the home numeracy environment and the home literacy environment are separate constructs (even though they have some shared variance; Napoli and Purpura, 2018), we view parental *belief about literacy* as a distinct

1 https://aspredicted.org/2YG_39S

construct from their knowledge about math. As such, we examined the relationship between these two constructs as an indicator of discriminant validity. We found evidence of discriminant validity for both types of parental knowledge. Specifically, parents' knowledge about early numeracy development was not correlated with their belief about their child's literacy abilities, $r(343) = 0.05$, $p = 0.342$. Additionally, parents' knowledge about early patterning development was not correlated with their perception of their child's literacy abilities, $r(343) = 0.09$, $p = 0.112$.

Parent-reported sources of their knowledge about early math development

To explore potential sources of parents' knowledge about early math development, we examined their reports of how they decided on their answers (see Supplementary Table S2 for additional details). Forty-three percent of parents' responses did not fit the coding scheme (e.g., some parents responded to the question with a single word). Of the 196 parents whose responses were coded, most mentioned that they thought about their experience with other children (54%) and/or their perception of their participating child's current abilities and their expectations for their participating child's math development (45%). Very few parents mentioned their knowledge of benchmarks or other information about children's early math development (16%).

Discussion and implications

The current study contributes to the development of a measure of early math development for preschool-aged children. As far as the authors know, this is the first paper to iteratively revise and develop a measure of parents' knowledge of early math development. Prior research shows there is variability in the frequency and complexity of math activities that parents engage in with their preschool-age children (e.g., Zippert and Rittle-Johnson, 2020). One potential source of this variability is parents' knowledge of early math development (Douglas, 2022). The current paper provides evidence for the internal consistency, test–retest reliability, and validity of the measure of parents' knowledge of early numeracy and patterning development among mostly college-educated, White US parents of 3- to 5-year-olds. Specifically, we had evidence of construct validity across two studies: numeracy items measured the same construct, and patterning items measured the same construct. Additionally, the final version of the knowledge measure demonstrates strong evidence for construct, convergent, and discriminant validity and some evidence of reliability for the numeracy and patterning subscales.

Limitations

Despite five rounds of measurement development and pilot testing, a limitation of the current study was that the measures of parents' knowledge about early numeracy and patterning development were only somewhat reliable, suggesting that additional measure development research could be beneficial. Additionally, we focused on validating separate subscales rather than a "math" measure. Notably, in Study 2, we found that the measures were substantially more reliable after parents received information about early math development. The inclusion of a related intervention between the time periods is uncommon for examining test–retest reliability; however, the evidence of high test–retest reliability suggests that the internal consistency of the measures was stable across the time points *despite* the information that parents received and that the measures can be used as predictors. Another limitation could be the dichotomous nature of the answer choices. Parents were given the option to choose "yes" or "no" to each item, but parents could have been unsure or wanted to choose "maybe." This decision may bias the results of our measure. Relatedly, while we noted how often parents who did the Think Aloud expressed uncertainty while completing the measure, we did not systematically measure parents' confidence or include a measure of parents' confidence in scoring their knowledge. Parents' low confidence in their knowledge about some skills could have reduced measure reliability. Finally, while we had some successes with recruiting a diverse sample (e.g., some studies included almost 50% of fathers and parents from almost all US states), most parents were White, had at least a Bachelor's degree, and had a household income of at least $45,000. This limits the generalizability of our findings.

Conclusion

Overall, the current study furthers the development and validation of a new measure relevant to the Home Math Environment (HME) which includes the math-related interaction, attitudes, and beliefs facilitated by parents of preschoolers. We provide details on a reliable and valid measure of parents' early numeracy knowledge that satisfies standards for the development of an adequate measure (Cooper and Schindler, 2003; Cohen et al., 2007; Joint Committee on the Standards for Educational and Psychological Testing, 2014). This allows for further research on the role parents' knowledge about early math development may play in their efforts to support their children's math development and sources of parents' knowledge about early math development. Such research could potentially inform interventions to support family members in providing meaningful and appropriate math learning experiences at home to support their children's math development and readiness.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Vanderbilt University Institutional Board. The patients/participants provided their written informed consent to participate in this study.

Author contributions

A-AD: project conceptualization, design, admin, data collection, data analysis, writing, reviewing, and revision. CM: project design–specifically measure revision, data collection, data analysis, writing, reviewing, and revision. BR-J: project conceptualization, design, admin, supervision, writing, and reviewing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1116883/full#supplementary-material

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Assembly-style making: How structured making serves as an on-ramp to creativity and engineering design

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Makerspaces, workspaces where families can explore materials and tools collaboratively, can provide an opportunity for creative expression and early engineering learning in community spaces. The present study examined a cardboard-focused museum makerspace that included an assembly-style activity. Assembly-style making uses instructions to support makers. Such activities have been critiqued as limiting creativity and engineering thinking. However, makers who are less comfortable in makerspaces may benefit from assembly-style activities helping to scaffold their entry into the space. We explored these criticisms and potential benefits of assembly-style making through developing case studies of video data taken by families in a makerspace. Visitors made creative and personally meaningful creations when engaged in assembly style making. Moreover, assembly-style making mediated a family less comfortable with making to get started in the space alongside ample evidence of families following engineering design processes. Contrary to popular belief, assembly-style making offers an important support to novice makers, without eliminating creativity and engineering design processes, and should be considered in the mix of activities available in makerspaces to support makers of all levels of comfort in making.

KEYWORDS

makerspace, family learning, informal learning, creativity, early engineering

1. Introduction

Drop-in makerspaces increasingly act as spaces of informal, out of school, early engineering learning (Martin, 2015; Children's Museum Pittsburgh & Institute of Museum and Library Services (IMLS), 2017). As more community spaces consider developing makerspace programming, a key question is the mix of activities available and how program design relates to potential learning outcomes (e.g., Marcus et al., 2021). In this brief research report, we share findings from case studies in a cardboard-focused museum makerspace. The present study centers the experiences of local Black, Hmong, and Indigenous families, groups that have been historically marginalized in the maker movement and literatures on family learning in makerspaces (see Vossoughi et al., 2016 for review). We examined interactions around 'Gravity Racer', which is an assembly-style activity that pairs instructions for building a cardboard vehicle with a ramp for testing. We developed case studies to consider:

1. Do families evidence creativity when engaging with an assembly-style activity (Gravity Racer)?
2. How might Gravity Racer support groups that feel less comfortable (more novice) with making?
3. How does engineering thinking emerge within the frame of interaction with Gravity Racer?

Recent research has provided insight into the learning outcomes possible in maker activities. Bevan et al. (2020) provided a framework for noticing and documenting learning in makerspaces. They identified five broad areas: initiative and intentionality, problem solving and critical thinking, conceptual understanding, creativity and self-expression, and social and emotional engagement. Each dimension had unique behaviors suggestive of learner progress, such as in the problem solving dimension where learners might iterate on their creation, seek ideas or tools to solve problems, and develop workarounds. Though developed with educators and students, the learning dimensions and behaviors associated with them also expand the possibilities of what behaviors constitute family learning in makerspaces.

Beyond varied learning dimensions, activity types may also lend themselves to different educative values to support the expertise of the maker. Here, Bevan's (2017) taxonomy of maker activities - assembly-style, creative construction, and tinkering - provided an additional lens for considering differences across making activities. Assembly-style activities share what and how something should be made, typically through provision of step-by-step instructions. Assembly-style activities may support the development of material and tool fluency, an essential step for novices to a particular maker practice to grow in skill and confidence in making. Creative construction and tinkering may support progressively more creative and self-initiated problem solving within making. These more open-ended styles were hypothesized to support maker agency and more authentic learning experiences (Dougherty, 2013; Martin, 2015).

Given the hypothesized potential limits on creativity and problem solving, not all informal scholars or practitioners feel comfortable with assembly-style activities. Concerned scholars voice that more structured maker activities may limit engineering learning potential and learner agency. These concerned voices paint a picture of children producing identical "tchotchkes" as a result of following predetermined, step-by-step instructions (e.g., Blikstein and Worsley, 2016; Davies, 2017). To allow for authentic engineering design cycles to occur and for youth to make items that are personally relevant, some makerspace designers have followed varied advice including creating entirely open-ended makerspaces (Clapp et al., 2017) or hiding away example creations (MakerEd, 2015). The current study sought to explore these concerns by examining an assembly-style activity across three dimensions: creativity, the interactions of novice makers, and engineering thinking, each described below.

Creativity in makerspaces is marked by playful exploration, responding aesthetically to the materials, connecting to personal interests, and using materials in novel ways (Bevan et al., 2020). By closely examining the processes and products of families interacting in the makerspace, we interrogated the extent to which an assembly-style activity limits opportunities for creative expression, or conversely, evidenced creativity. Potential benefits and downfalls of creative constraints have been documented in a wide range of literatures beyond makerspaces (Medeiros et al., 2014; Roskes, 2014; Acar et al., 2019). Perhaps more closely aligned with the learning potential of makerspaces, long debates considering the merits of didactic versus discovery approaches to learning evidenced that structured activities can support learning (Mayer, 2004; Kirschner et al., 2006), though others continue to find advantages to exploratory over didactic approaches (Bonawitz et al., 2011). These literatures hint at the possibility that creativity and structure are not related in a strictly linear fashion where more structure always results in less creativity. What might this look like in assembly-style making practices?

In contrast to the perceived limits on creativity, a benefit of assembly-style activities may include supporting novice makers in learning new practices (Bevan, 2017). Improved material or tool fluency relies on novice makers getting started in the space. Instructions in an assembly-style activity may be an important scaffold to getting started. However, how family groups less comfortable with making get started together is not well characterized. New evidence suggests that emerging engineering interest may act as a family-level phenomena (Pattison et al., 2020), suggesting that social interactions between family members play a role. Whereas some practitioner guides, such as the Youth Makerspace Playbook, provided scripts that discourage using instructions to overcome uncertainty in a makerspace (MakerEd, 2015, p. 72), the present study investigated a different approach in a makerspace that included an assembly-style activity.

Finally, as a form of early informal engineering education, there is interest as to whether makerspace activities support exposure to and early practice of engineering design processes. The engineering design process for young learners (plan, create, test, and iterate) is meant to echo the practices that engineering professionals follow to solve problems (Moore et al., 2014; Major, 2018). Assembly-style activities have been criticized as potentially limiting engineering thinking by having a set of instructions that diminishes a visitor's need to plan, iterate and problem solve on their own (American Society for Engineering Education, 2020). However, Gravity Racer was designed with the intention that the activity hinted at the possibility of following the engineering design process. Visitors are supported in their plan (icon-based instructions for making a car) before having the opportunity to create (families create a vehicle), test (families can test their vehicle on the ramp) and iterate (families improve on their vehicle design). The potential for visitors to follow such a design process within the designed elements of the activity does not mean that families follow such a process. Thus, we also sought to document how families approached Gravity Racer as an assembly-style activity suggestive of engineering design processes.

Combined, the present study explored new frames for considering the benefits and limitations of assembly-style maker activities. The current study primarily examined video data of family engagement in a makerspace to develop case studies to interrogate Gravity Racer, which was designed as an assembly-style activity, along the dimensions of (1) creativity, (2) the approach of novice makers, and (3) engineering thinking. Given how widespread questions around the value of assembly-style activities run among makerspace educators and designers (MakerEd, 2015; Blikstein and Worsley, 2016; Clapp et al., 2017; Davies, 2017) developing cases that evidence creativity and engineering thinking within the frame of assembly-style activities is an important contribution in expanding our understanding of family learning in makerspaces more broadly.

2. Materials and methods

2.1. Cardboard City exhibition and gravity racer

Cardboard City was an indoor makerspace exhibition at the Science Museum of Minnesota. It featured a mix of activity styles within a city theme. The space was relatively unfacilitated; that is, while there were substantial supports needed to maintain materials and cleanliness of the space, a facilitator was not leading the visitors through the activity.

The activity area focal to the present study was the Gravity Racer activity. The Gravity Racer included a supply table where groups gathered pre-cut wheels, axles, and cardboard to create the vehicle body. Icon-based instructions (see Figure 1) demonstrated how to make a vehicle with the provided materials. Nearby, the inclusion of a ramp was an intentional design choice meant to spur engineering design cycles within the activity. The ramp accommodated multiple vehicles at a time, featuring lanes of different heights and texture. A simple lever released the vehicles down the ramp.

2.2. Data collection and analytical approach

The museum makerspace hosted Cardboard Family Night Events in partnership with community organizations that served primarily families that identified as Black, Indigenous, People of Color (BIPOC). About 90% of adults who attended a Cardboard Family Night Event identified as BIPOC. All adults attending Cardboard Engineering Family Night events were invited to participate in a brief survey about their group's experience in the makerspace, their own interest in making, and demographic items.

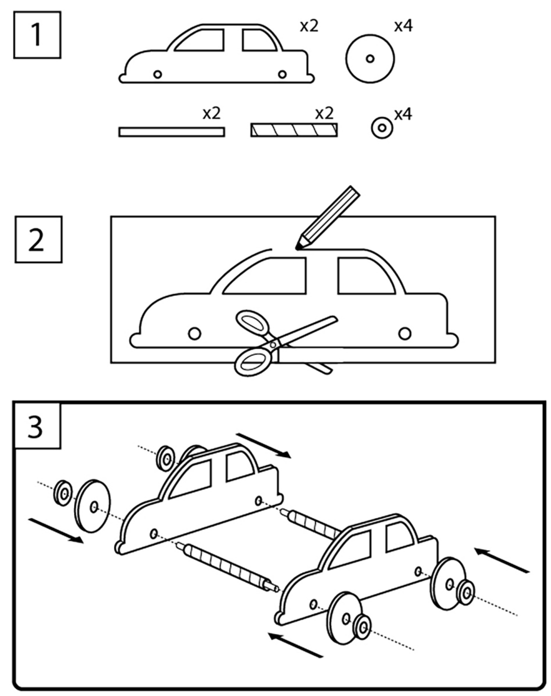

FIGURE 1
Icon-based Instructions for the Gravity Racer activity. The graphics depicted assembly-style instructions for making a canonical car.

Families were given the option to participate in video-recording their interactions in the makerspace. Groups were given GoPro Hero 4 or GoPro Hero 8 cameras, with tripod mounts. Families were encouraged to turn on and off the camera as they wished, with a goal of capturing at least 20 minutes of video. In addition, follow up interviews were conducted and video-recorded, capturing participants' reflections of their experience in the makerspace. The combination of survey, video data of time in the makerspace, and follow up interviews with participating families allowed us to develop case studies with a subset of families.

In general, we approached the analysis seeking triangulation across data sources to support trustworthiness of the findings (Shenton, 2004; Carter et al., 2014). Moreover, in the case of video data, video data sessions allowed all authors to contribute to the interpretation of emerging findings (Jordan and Henderson, 1995; Huma and Joyce, 2022). Survey and interview data that supported the key findings from the video data bolstered confidence in the findings that emerged from the cases described below.

2.2.1. Analysis of creativity

The Gravity Racer icon-based instructions depicted a canonical car. It had two axles, four equally sized and balanced wheels, and a canonical car shape. Given that one concern around assembly-style activities is that makers will simply "copy" the instructions, we examined video across groups for products of the Gravity Racer activity. We operationalized creativity as a willingness to diverge from the plans laid out in the Gravity Racer instructions.

2.2.2. Case selection: Novice makers

To examine how Gravity Racer worked for families less comfortable with making, we identified adults that were in the bottom quartile for interest in making on the event survey, meaning they endorsed mostly "No" or "Kind Of" to questions about their enjoyment of broad making activities at home (e.g., fixing things, doing crafts). From there, we identified the 'Noticing Stations' case which involved a mother, Deja and her three children Jada (age 9), Lela (age 6), and Zuri (age 2). We selected this case because the caregiver reported not being personally interested in making on the event survey, and in an interview Deja said of being creative, "*My children yes, me no – do not like it, I'd rather read a book, watch a movie, but I have little girls that wants to decorate which actually we just did it the other day [at home].*" We focused on how the group got started in the space and how they approached making from a stance of creativity and engineering thinking.

2.2.3. Case selection: Engineering design process

Similarly, to examine engineering design processes we sought to identify a family that interacted with the Gravity Racer ramp. We identified the 'No-body Car' case which involved a set of parents, Kao and Mai and their four children, Eve (age 6), Tou (age 5), Fue (age 2), and Paj (an infant). Analysis focused primarily on Eve's design and testing of her 'No-body car' which was identified during the analysis of creativity described in section 2.2.1. Eve's engagement, with support from Mai allowed for examination of their entry into the activity, the creativity of the No-body design, and the engineering design processes present within the context of the assembly-style activity.

3. Results

3.1. Creativity in assembly-style making

We first sought to explore criticism of assembly-style activities through the lens of creativity. Figure 2 captures examples of products of the Gravity Racer activity, documenting the ways in which they differed from the canonical vehicle included in the instructions. Importantly, across the families that participated in the video research when Gravity Racer was present ($n = 24$), we see variation across their creations in terms of the number of axles, configuration of the wheels, shape of the vehicle body, and in one example a complete re-mixing of the Gravity Racer materials to make a 'puppet' character. Thus, providing icon-based instructions suggestive of a canonical car did not limit visitors to just making copies of the suggested design. In fact, though each product of making in Figure 2 highlights a particular feature, the products shown vary across multiple dimensions from the support given in the instructions. In this way, we saw visitors making personally meaningful creations even within the frame of an assembly-style activity.

3.2. Noticing stations case

With evidence that creative expression was possible within the Gravity Racer activity, we turned to a potential benefit of assembly-style activities: support for those less comfortable with making. In reflecting on their time in the space as a family, Deja self-identified her role as a supporter of her creative children, saying *"I do not feel like [.] I do not know creativity in that aspect, like building something, just does not flow naturally to me, so that's why like I'm a good supporter."*

In Figure 3 we trace the family's entry into the makerspace focusing particularly on Deja and Lela as the two family members that spent the most time with the Gravity Racer activity.

In line 1.05 (which occurred approximately one minute after Deja began to walk through the space) Lela expressed apprehension about "what to use," which the adult verbally labeled as "overwhelmed." In responding to this need, Deja immediately pointed to and then approached Gravity Racer (Figures 3B,C). Multiple elements – the size of the ramp, the supply table, the instructions on the wall – may have supported the adult in noticing this "station" (Figure 3, line 1.18) which offered a path to alleviate feelings of not knowing "what to use" (line 1.05) in the space. Lela expressed interest in making a car, but the group did not immediately act on this interest as they considered other activities.

After several minutes, Lela took up Deja's offer to make a car (line 1.31). In moving back to the supply table (Figures 3D,E), the icon-based instructions mediated Deja and Lela getting started together, with each pointing towards the assembly-style instructions to begin to collect the materials for making a car. Furthermore, it is in this approximately 12 minutes of making together that Deja begins building her own car. Deja suggested and then enacted a change from the canonical car design to trace her own hand while Lela and Zuri follow her lead. Thus, while Deja reported feeling relatively uncomfortable with being creative, it is in the assembly-style activity where we see Deja take on the role of maker; and problem solve for solutions in making the body of the vehicle.

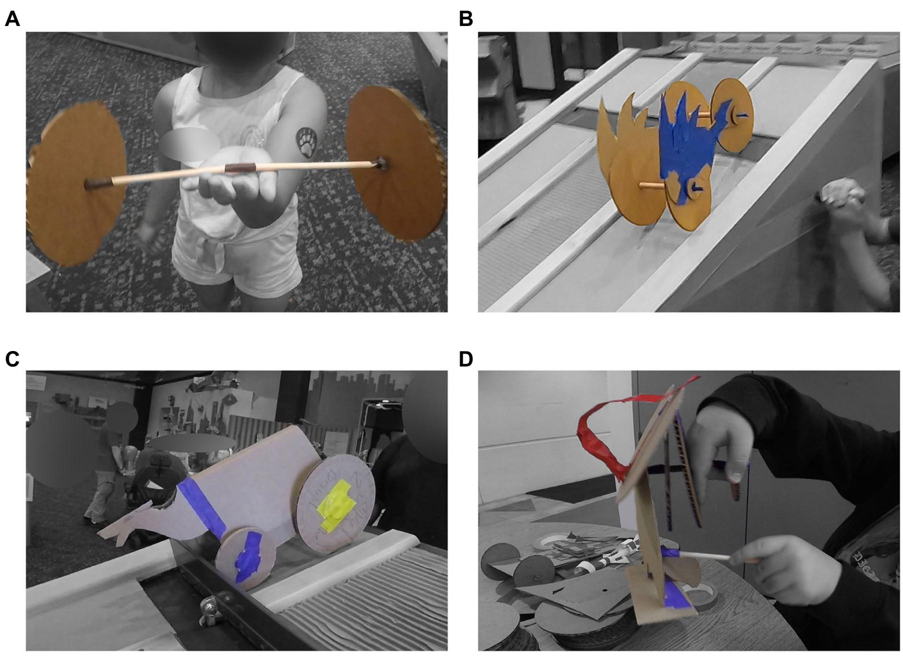

FIGURE 2
Creative Products of Gravity Racer. These examples highlight just some of the creative variation seen across groups. Panel **(A)**: No-body car (differs in axles), Panel **(B)**: Sonic car (differs in body shape), Panel **(C)**: Viking car (differs in wheel configuration), Panel **(D)**: Puppet (complete remix of materials).

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Line First image: Lela is overwhelmed
1.01 Lela: ((walks up to parent with arms out by sides, palms
1.02        up, shrug posture))
1.03        Deja, I don't know [what to use[A]
1.04 Deja:                       [((turns to Lela))
1.05        You don't know what to use?
1.06 Lela: ((turns to open area in makerspace))
1.07 Deja: Are you overwhelmed?
1.08 Lela: [Yes I am
1.09        [((nods slightly))
1.10 Deja: You're overwhelmed
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A

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     Second image: Deja points to Gravity Racer
1.11 Deja: Well [look[B] they got          ]
1.12              [((points towards ramp))]
1.13        Do you wanna try to make a car?
1.14 Lela: ((walks off in direction of Jada))
1.15 Deja: [C'mon Zuri
1.16        [((walks towards Gravity Racer supply table))
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B

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     Third image: Deja shares discovery of Gravity Racer
1.17 Deja: ((arrives at Gravity Racer supply table))[C]
1.18        Hey Jada, Lela,  It's a station over here. [They're not listening to me
1.19                                                    [((walks toward Jada and Lela
1.20        Where's the little one? Hey little one
1.21        ((arrives at table Jada is working at and Lela is nearby))
1.22        Hey Jada it's a station over there that'll show you how to make a car
1.23 Jada: Ok
1.24        ((turns away from Deja, reaches for tool on table))
1.25 Lela: I want to do one
1.26 Deja: You want to make a car?
1.27 Lela: [Yeah
1.28        [((nods))
1.29 Deja: Ok right it's a station. Oh what's this station over here?
1.30        [((moves toward theater activity))
```

C

```
     Interlude: 8 minutes engaging with activities near Jada
1.31 Lela: Deja, [can you show me how to (.) like (.) make a car?
1.32 Deja:        [((Deja looks at Lela))
1.33        Yep let's go build a car
1.34        ((turns to Jada))
1.35        We fittin to go make a car, we'll be right back since you working so hard on your background, ok
1.36 Jada: ok

     Fourth Image: Deja points to the instructions
1.37 Deja: Hey Lela (2.0) the car is over here
1.38        ((Deja and Lela walk and meet at Gravity Racer supply table))
1.39 Lela: Gotta make all these cars
1.40 Deja: ((looks up, towards icon-based instructions))
1.41        Ok, [so         ]
1.42 Lela:      [Gotta make] (.) two
1.43 Deja: No (.) Yeah uh no it says we [need[D] four (.)              ]
1.44                                      [((points at instructions))]
1.45        Here's the instructions.
1.46 Lela: Four wheels
1.47 Deja: We need four wheels
1.48 Lela: [One ((counting))
1.49        [((grabs wheels from container))
1.50 Deja: and we need four big ones and four small ones. [So these are four big ones          ]
1.51                                                       [((picks up wheels Lela picked out))]
1.52        now where's the four small ones?
1.53 Lela: [One, two, three and four
1.54        [((grabs wheels from container))
```

D

```
     Fifth image: Lela points to instructions to clarify materials with Deja
1.55 Deja: Ok, now it [says we need two           ] [of these              ]
1.56                   [((points to wooden dowels))] [((picks up 2 dowels))]
1.57 Lela: And we need [these right
1.58                    [((Grabs and holds up the small circular piece))
1.59 Deja: No we don't need that one.
1.60 Lela: Oh I [thought[E]                     ]
1.61             [((points to icon-based instructions))]
1.62 Deja: That's like
1.63 Lela: Those are the little tiny things
1.64 Deja: Ok yeah, do two, four of those.

     Group continues to make together for an additional 11 minutes
```

E

FIGURE 3
Key Moments in the Noticing Stations Case. Panels **(A–E)** display still images from the video of the group's entry into the makerspace, alongside a transcript of the group's verbal interactions that align with these frames.

That is not to say assembly-style making in Gravity Racer completely resolved points of tension for those less comfortable in making. When asked if the activities felt like engineering Deja responded,

> "It did, and I was aggravated. I was trying to make a car and for the life of me I do not know how to trace. Yeah, I cannot draw. [audio cuts out] And I was like, I was really thinking, man, people who have to build stuff, I commend them."

Nonetheless, the ease with which the group noticed the Gravity Racer activity, pointing to it (line 1.12) to alleviate Lela's feelings about "what to use" and then working together through the

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accompanying instructions suggests that this assembly-style activity did support this group in having a way to get started in the makerspace.

3.3. No-body car case

We next turned our focus to engineering design processes. Eve's car was highlighted in Figure 2 as an example of creative design. Figure 4 traces Eve as she went through an engineering design process – plan, create, test, and iterate. For Eve, the plan and create steps happened intuitively. From the video data available, there was no recorded sequence of her family interacting with the instructions. Instead, the ramp and example vehicles available in the space left behind by other visitors hinted at the possibility of making vehicles. In Mai's interview she recalled,

> ".. [Eve] noticed that my boys were playing with the ramp. She wanted to come up with something that would roll down the ramp. And then it got to where she wanted to see whose is the fastest, or what can she build that can go down the ramp the fastest, kinda like a race. So, that's why everyone just turned their attention to the ramp of, hey, I wanna build something. I wanna see how fast it can go. I wanna build the fastest."

Eve's goal displayed an engineering mindset in building for efficiency. We investigated this case further by considering parallels to engineering design processes.

Mai supported Eve in her planning and creation, though she voiced some skepticism about the plan to include no vehicle body in the design (Figure 4, line 2.06). Following the completion of the creation stage, Eve tested her design with support (Figure 4, lines 2.21–2.35). Eve later tested the no-body car another time, with Fue

```
Line First image: Plan & Create, Eve making the car with support from Mai
2.01 Mai: ((holds axle with a single wheel))
2.02 Eve: ((holds second wheel up to end of axle))[A]
2.03 Mai: Well what are you gonna put?
2.04      [What're you gonns put?             ]
2.05      [((motions to middle of the axle))]
2.06      You're just gonna do [this?
2.07                           [((moves creation out of camera view))
2.08 Eve: [Yeah
2.09      [((smiles))
2.10 Mai: Uh I don't think it's gonna be stable like that, unless you tape
2.11      this side here too [cuz ()     ]
2.12 Eve:                    [Yeah, yeah] that too m:hm::
2.13      Fue (.) like [what like kinda what we did with Fue's but ()]
2.14                   [((points to Fue's bus))]
2.15 Mai: Ok

     Second image: Eve and Mai present creation to the camera
2.16 Mai: What is that?[B]
2.17 Eve: Um::
2.18 Mai: You're gonna try to balance it (1.0)
2.19      Here ready, let's go
2.20      ((walks with Eve towards ramp))

     Third image: Test, Eve tests her creation on the ramp
2.21 Mai: Oop you might have to to do it both, put it in between
2.22      [put it in between
2.23      [((demonstrates with bus sideways))
2.24 Eve: ((places creation on ramp))
2.25 Mai: Yep
2.26 Eve: Like that
2.27 Mai: Do you think it's gonna work?
2.28 Eve: [((vocalizes mimicing "I don't know"))]
2.29      [((shrug))                           ]
2.30      [Move the cars              ]
2.31      [((points to end of ramp))]
2.32 Mai: ((clears ramp of other cars, turns back to Eve)) [C]
2.33 Eve: ((releases car which moves down the ramp))
2.34 Mai: Wa::: it worked!
2.35 Eve: ((smiling, claps))

     Fourth image: Iterate & Test, Eve tests out her new creation
2.36 Eve: Look here
2.37 Mai: ((releases Fue's bus down the ramp))
2.38 Eve: [Look, Mom                  ]
2.39      [((sets creation on ramp))]
2.40      I hope it works! Mom move the stu-
2.41      ((moves creation to different lane on ramp))
2.42      This is a small one
2.43      ((releases car which moves down the ramp)) [D]
```

A, B, C, D

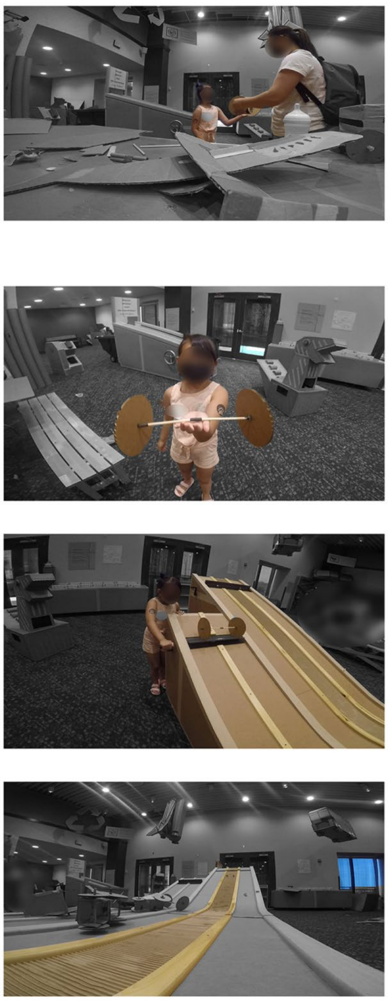

FIGURE 4
Key Moments in the No-body Car Case. Panels **(A–D)** display still images from Eve's interactions with Gravity Racer, alongside a transcript of the group's verbal interactions that align with these frames.

grabbing the car at the end of the ramp. This action prompted Eve to collect supplies to make a smaller iteration of the same design and test that iteration (Figure 4, lines 2.36–2.43). Thus, the case evidenced many instances of engineering thinking and demonstrated that the entirety of the engineering design process (plan, create, test, iterate) were possible within the Gravity Racer activity.

4. Discussion

The present study sought to explore assembly-style making along dimensions of 1) creativity, 2) support for novices, and 3) engineering thinking. We developed case studies around two families interacting with a cardboard-focused makerspace in a museum setting. Given concerns that assembly-style activities, like Gravity Racer, that include instructions would eliminate creativity and limit engineering thinking, rich video counterexamples provided compelling evidence that assembly-style activities may play an important role when considering the mix of activities available to families in makerspaces.

Revisiting the learning dimensions possible in makerspaces, we found that groups captured many instances of creative expression while they were engaged in an assembly-style activity. Our findings serve to blur the lines between categories within Bevan's (2017) taxonomy of maker activities. The instructions for Gravity Racer and pre-cut wheels and axles lend the activity to assembly-style forms of making, but some aspects of the activity such as the fashioning of the vehicle body lean more towards creative construction. In the 'Noticing Stations Case' Deja suggested and then enacted a creative solution of tracing her hand to make the body of the vehicle. Likewise, Eve took a creative approach in the 'No-body Car Case', designing a vehicle with only one axle and no car body. Even with instructions present in the space (and Deja and her family attempting to follow the instructions closely) groups engaged creatively in their making.

We were interested in how an assembly-style activity, like Gravity Racer, might support novices in the space. For this study, we defined novices as individuals who self-reported primarily "No" or "Kind of" when surveyed on their enjoyment of making (building things, fixing things, etc.). By focusing on a group in the 'Noticing Stations Case', we noted how Deja responded immediately to Lela feeling "overwhelmed" by pointing to the Gravity Racer activity. Later, when they take up making together the instructions mediated interactions between caregiver and child, with each pointing to and gathering materials together. That is not to say that having instructions present in the space means that everyone seeks them out and follows them. Eve relied mainly on example pieces, which have also been discouraged in the maker literature (e.g., MakerEd, 2015). This group never interacted with the instructions on camera (groups were free to turn the camera off and did so over the course of their time in the space). This suggests that while the Gravity Racer clearly lends support consistent with an assembly-style mode of making, makers may take on tasks more consistent with creative construction or even tinkering over the course of making in a free choice space. Instructions provide one way of getting started but not the only way to approach the activity.

Groups engaged with the Gravity Racer also engaged in engineering thinking. Deja and Lela used the instructions to plan, and then had to iterate and problem solve around ways to make the body of the car. Eve tested multiple creations on the ramp alongside her family members. This particular assembly-style activity, Gravity Racer seemed ripe for fostering skills related to engineering thinking.

One advantage of making with a widely available material like cardboard was that groups could continue making at home. In fact, we heard from several groups involved with the larger study that their children had continued making with cardboard at home– including from Deja and Mai. We are less certain how caregivers who are less confident about making (as in the 'Noticing Stations' case) might engage in making at home, with or without the use of icons and instructions for support. This suggests a productive line of inquiry for future research into assembly-style activities.

In recent years, makerspaces have been seen as opportunities to advance equity in informal learning settings (Calabrese Barton et al., 2017). This analysis was part of a larger project centering BIPOC family experiences in making. While the present study utilizes that data, we were not aiming to make a claim about BIPOC families in particular. Several studies on equity in makerspaces focus on youth working with educators (e.g., Calabrese Barton et al., 2017; Sengupta-Irving and Vossoughi, 2019). More work could consider family interactions in makerspaces, building off insights around creativity or engineering thinking in the present study, or the work of other researchers considering family learning (e.g., Tzou et al., 2019).

Our analysis is limited in that the case selection focused on just two families that in some ways represented a best-case-scenario perspective on features of interest, namely creativity, getting started in the makerspace, and engaging in engineering design processes. This approach was warranted given that most advice in maker education prioritizes tinkering over assembly-style activities. Further replication with other assembly-style activities would bolster confidence in the strengths and weaknesses of assembly-style making. A second potential limitation of the present study was that the assembly-style activity directly included a clear means to test one's creation in the form of a ramp. We hypothesize that including this 'test bed', designed to be both fun and encourage iterations, is an important part of noticing the potential of the activity and offering multiple entry points into the engineering design process. Future studies might consider if the evidence supporting assembly-style making is as strong without such a designed element present.

We conclude that makers may benefit from a mix of activities being available in the makerspace. While the literature elsewhere has shared the benefits of tinkering, the present study demonstrated that providing assembly-style activities may address visitors' comfort in making and alleviate potential hesitancy in how to start. Makers can be creative and practice or engage in engineering thinking within the frame of an assembly-style activity. We encourage practitioners to tinker with assembly-style activities in their own spaces, see how makers use those activities to get started, and to go farther than the directions. We also encourage other researchers to look at these activities to understand how they operate in a space – for instance, how do families with multiple levels of experience, or multiple interests, use activities like these? Are some assembly-style activities structured in ways that support less or more creativity, or work worse or better as ways to get started in the space? Our exploration of assembly-style activities suggests that they are appropriate to include, but more can be understood about the many roles assembly-style making can play in a multi-generational makerspace.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by Heartland Institutional Review Board. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin. Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

Author contributions

MB, MG, and SL contributed to the conceptualization and design of the study. BS led the concept development and design of Cardboard City. SL led the analysis and prepared the first draft of the manuscript. MG and SL prepared the figures. All authors contributed to video data analysis and manuscript revision, all read and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Malleability of spatial skills: bridging developmental psychology and toy design for joyful STEAM development

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Previous research has established that advances in spatial cognition predict STEAM success, and construction toys provide ample opportunities to foster spatial cognition. Despite various construction toy designs in the market, mostly brick-shaped building blocks are used in spatial cognition research. This group of toys is known to enhance mental rotation; however, mental rotation is not the only way to comprehend the environment three-dimensionally. More specifically, mental folding and perspective taking training have not received enough attention as they can also be enhanced with the construction toys, which are framed based on the 2×2 classification of spatial skills (intrinsic-static, intrinsic-dynamic, extrinsic-static, extrinsic-dynamic). To address these gaps, we compile evidence from *both* developmental psychology *and* toy design fields to show the central role played by mental folding and perspective taking skills as well as the importance of the variety in toy designs. The review was conducted systematically by searching peer reviewed design and psychology journals and conference proceedings. We suggest that, over and above their physical properties, construction toys offer affordances to elicit spatial language, gesture, and narrative among child-caregiver dyads. These interactions are essential for the development of spatial skills in both children and their caregivers. As developmental psychology and toy design fields are two domains that can contribute to the purpose of developing construction toys to boost spatial skills, we put forward six recommendations to bridge the current gaps between these fields. Consequently, new toy designs and empirical evidence regarding malleability of different spatial skills can contribute to the informal STEAM development.

KEYWORDS

informal STEAM development, toy design, construction toys, mental rotation, mental folding, perspective taking, spatial cognition

1. Introduction

The acronym STEAM (Science, Technology, Engineering, Arts, and Mathematics) is usually collocated with the terms "learning" or "education." However, these terms often have formal and technical connotations. On the other hand, informal toy play sessions provide an alternative context to incorporate STEAM improvement into the daily routine (Bergen, 2009; Toub et al., 2019; Martin and Murphy, 2022) since out-of school activities are just as important as in-school activities for STEAM development (Gözüm et al., 2022), and children spend a considerable amount of time playing with toys outside of school (Giddings and Halverson, 1981; Halpern et al., 2007; Bekker et al., 2009). Research demonstrates that playing with construction toys, which consist of units assembled in multiple configurations (Brosnan, 1998; Stannard et al., 2001; Weller et al., 2008), predicts achievement in STEAM-related disciplines (Wai et al., 2009; Trawick-Smith et al., 2016; Borriello and Liben, 2017). The primary mediatory factor in this relationship is spatial cognition, which refers to the ability to interact with the vicinity in a three-dimensional way, physically or mentally (Vasilyeva and Lourenco, 2012; Newcombe et al., 2013; Bower et al., 2020a). Children employ spatial cognition in many daily activities, such as tool use, games, route finding, and school-related tasks.

Developmental psychology and toy design are the two fields relevant to using toys for improving spatial cognition and STEAM success. However, these fields are currently not well connected. On the one hand, developmental psychology studies are conducted mainly with a limited variety of toys (e.g., building blocks); alternative toy designs are not considered for enhancing spatial development, yet their affordances may contribute to different aspects of spatial cognition. Although there were some attempts to conduct research on the different construction toys, they were shadowed with methodological concerns. For instance, Vander Heyden et al. (2017) assessed the improvement in the various spatial skills with a pre- and post-test intervention that involved various toys; however, the toys were not distributed systematically in the training procedure. Participants played with several toys in each training session and their cumulative effect was tested at the post-test phase. Hence, the separate effect of each training session and each toy design on the post-test results was obscured. In another study, Ralph et al. (2020), magna tiles toy was used rather than typical building blocks. Yet, there was no emphasis on this toy's affordances (i.e., how its physical attributes support spatial cognition). It was chosen solely as a context to elicit spatial play by mother and child dyads.

On the other hand, toy design research rarely considers evidence from developmental psychology regarding toy development and child interaction. The ones that involve psychology theories sometimes lack depth in their conceptual definitions. For instance, Geurts et al. (2014) developed digital cubes to improve perspective taking skill however the term was defined in a limited way as detecting right and left of another agent. In another study, Rigo et al. (2016) criticized the repetitive cubicle design of building blocks in the market, and proposed an alternative design that consists of various polyhedrons. However, they did not provide a rationale to their new design in relation to development of spatial skills.

Instances above demonstrate the lack of a dialog between developmental psychology and toy design literatures. The current review aims to highlight and strengthen this connection, which is a first attempt for both lines of literature. While illustrating the gaps, first the existing evidence on the malleability of three different spatial skills (i.e., mental rotation, mental folding, and perspective taking) will be presented. Then some toy design examples will be shared, in relation to their potential to foster these three spatial skills. Last, six recommendations will be provided for future research to highlight what can be done further regarding toy design. Also a benchmark of construction toys will be presented based on their contribution to spatial skill development. The upshot of this review is to combine the perspectives of developmental psychology and design research to address how to diversify the spatial affordance of toys for child-caregiver dyads. Although some existing studies attempt to bridge the psychology and the design literatures (Hekler et al., 2013; Beşevli et al., 2022), no study so far has focused on the spatial cognition domain in relation to toy design.

2. State of the art

Playing with spatial toys such as blocks and puzzles offers opportunities for exploring different object orientations and viewer perspectives (Casey et al., 2008; Pirrone et al., 2015; Vander Heyden et al., 2017). Similar mental exercises are required for STEAM fields (Hinze et al., 2013; Uttal et al., 2013b; Polinsky et al., 2022); consequently, playing with those toys facilitates STEAM development (Wolfgang et al., 2003; Hanline et al., 2010; Taylor and Hutton, 2013).

Three spatial skills are potentially related to STEAM success. First, *mental rotation,* which refers to changing the orientation of an object's mental representation at a certain angle (Shepard and Metzler, 1971; Hawes et al., 2015; Lauer et al., 2015). Second, *mental folding,* which stands for changing the physical properties of an object while moving it in a given space, for example, transforming a two-dimensional paper into a three-dimensional structure (Atit et al., 2013; Harris et al., 2013b; Burte et al., 2017). Third, *perspective taking,* which refers to the ability to see a scene from another point of view (Kessler and Rutherford, 2010; Erle and Topolinski, 2015; Gunia et al., 2021). Previous studies have mainly investigated mental rotation training, while mental folding and perspective taking skills have been largely overlooked (Cherney et al., 2014; Newcombe and Shipley, 2014; Vander Heyden et al., 2017). Thus, training in those two spatial skills needs attention considering their contribution to STEAM development (Mix and Cheng, 2012; Newcombe, 2017; Hodgkiss et al., 2018).

While it is expected that developmental psychology literature should use and compare various toy designs for their impact on different spatial skills, design studies should also incorporate theoretical frameworks of developmental psychology into the toy design process. However, these frameworks may not be readily available for toy designers to access and interpret (Hall et al., 2022). Furthermore, the reasons why toy producers add certain features to their designs and what particular points they consider while designing construction toys are not immediately transparent, even though there may in fact be several theoretical foundations employed in the current toy designs (DeCortin, 2015). Therefore, enhancing the spatial characteristics of the construction toys is an important step in bridging the gaps observed between theory and practice (Hekler et al., 2013; Borriello and Liben, 2017; Yang et al., 2020). Through this review paper, we aim to provide the following recommendations to the design field by revisiting both strands of literature:

1. Include mental folding components.
2. Design large-scale toys to facilitate perspective taking skill.
3. Consider the entire user experience, in addition to the physical properties of the toys.
4. Embrace multiple personas (i.e., adults and children).
5. Add features to elicit spatial language, narrative, and gesture use.
6. Avoid using extremely themed products.

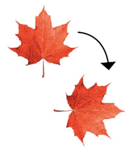
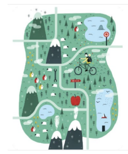
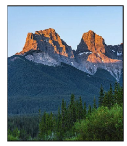
3. Method

A literature review was conducted systematically to assemble various research studies written about malleability of spatial skills, STEAM education, and toy design between the years 1969 and 2022. In this review, we used both expansive databases like Google Scholar, Elsevier, ProQuest, PubMed and EBSCO, and domain specific databases like PsycInfo and ACM digital library. The keywords used to explore relevant articles were "malleability," "spatial cognition," "perspective taking," "mental rotation," "mental folding," "construction toys," "building blocks," "spatial training," "spatial intervention," "spatial input," and "informal STEAM education." We used the handles "AND," to affiliate search terms between each category, and "OR," to connect search terms within each category.

All articles examined in the process of the literature review were analyzed based on their abstracts by the first three authors. Then based on the relevance of each article to the current concept of this paper, articles were either removed from the reference list or kept to be further analyzed to support the research of this paper. While the articles were being reviewed, their reference lists were also examined to expand the scope of the literature review through snowballing.

The publications included in the literature search would be considered suitable if they met the following criterion: (a) articles focusing exclusively on malleability of spatial skills or construction toy design, (b) papers only published in English, and (c) papers that are published in peer-reviewed journals. Papers were excluded based on the following criteria: (a) works that are not accessible through the databases, (b) works that did not address the relationship demonstrated in the objectives of this paper, which are construction toys and spatial skill development, (c) any unpublished data, and (d) and short communications, and editorials.

TABLE 1 2×2 classification of spatial skills and examples [adapted from Uttal et al. (2013a)].

Spatial skill	Definition	Example
Intrinsic-static	Apprehending objects, paths, or spatial placements over distracting background information	
Intrinsic-dynamic	Bringing objects into more complex placements, mentally rotating objects or transforming from 2D to 3D	
Extrinsic-static	Recognizing and apprehending spatial principles relatively to other objects such as horizontality and verticality	
Extrinsic-dynamic	Mentally representing an environment in its full shape from various perspectives	

4. Spatial cognition

Spatial cognition is an essential ability for many species as it enables individuals to understand the three-dimensional world better. Skills that make up spatial cognition reveal themselves in two ways: Tool making and navigating in the environment (Ehrlich et al., 2006; Morganti et al., 2009; Newcombe et al., 2013). Thus, spatial cognition directly connects to daily tasks like understanding a map or organizing a wardrobe (Vasilyeva and Lourenco, 2012; Meneghetti et al., 2015; Bower et al., 2020a). Aside from these uses, spatial skills are related to school readiness (Verdine et al., 2014) and numerical cognition (Newcombe et al., 2015), consequently predicting achievement in STEAM disciplines (Wai et al., 2009; Taylor and Hutton, 2013; Uttal et al., 2013b).

The conceptual scope of spatial cognition must be clarified since various definitions exist in the literature and a common framework is yet to be established (Resnick and Shipley, 2013; Newcombe and Shipley, 2014; Mix et al., 2018). A comprehensive and empirically tested theory, which is supported by neural (Creem et al., 2001; Wraga et al., 2005; Lambrey et al., 2011) and behavioral findings from different age groups (Taylor and Hutton, 2013; Vander Heyden et al., 2017; Hodgkiss et al., 2018), classifies spatial skills through a 2×2 matrix. This matrix is based on the mental representations' static/dynamic and intrinsic/extrinsic properties (Uttal et al., 2013a; Yang et al., 2020; Bower et al., 2020b) (see Table 1).

Static spatial cognition allows individuals to interpret non-moving objects, while dynamic spatial cognition enables them to follow changing stimuli. Research shows that static and dynamic spatial cognition have different underlying mechanisms (Kozhevnikov et al., 2002, 2005). The other axis of the 2×2 matrix includes intrinsic and extrinsic spatial representations. Intrinsic spatial cognition refers to understanding within object relationships, and it is a key skill for tool use (Harris et al., 2013a; Newcombe and Shipley, 2014; Frick, 2018). Extrinsic spatial cognition refers to understanding the relationship between objects, which is necessary for navigation (Kinach, 2012; Atit et al., 2013; Newcombe et al., 2013). Research indicates that extrinsic and intrinsic spatial skills follow different neural pathways (Chatterjee, 2008; Li et al., 2019; Gunia et al., 2021), and have separate mechanisms (Huttenlocher and Presson, 1973; Hegarty and Waller, 2004; Newcombe et al., 2013; Hodgkiss et al., 2018). Vander Heyden et al. (2017) explain this mechanism via different strategies used by the participants for mental transformation and perspective taking tasks: object transformation and viewer transformation, respectively. Through the object transformation strategy, participants tend to mentally change the target object's orientation without changing their position. On the other hand, during the viewer transformation strategy, participants mentally rotate themselves in a given space and change their frame of reference to perceive an object from a different point of view (Hegarty and Waller, 2005; Harris et al., 2013a; Vander Heyden et al., 2017).

In the current review, we will focus on the informal training tools (i.e., toys) for the two intrinsic dynamic spatial skills: mental rotation and mental folding, and an extrinsic dynamic skill: perspective taking. The literature is rich in examining intrinsic dynamic spatial relations (Frick et al., 2013a; Uttal et al., 2013a; Newcombe and Shipley, 2014). However, existing studies primarily focus on mental rotation; overlooking the mental folding skill (Atit et al., 2013; Harris et al., 2013a; Hilton et al., 2022). Furthermore, there is a lack of training for improving extrinsic dynamic spatial skills (i.e., perspective taking) (Mori and Cigala, 2015; Vander Heyden et al., 2017; Tian et al., 2021). Perspective taking skill is crucial as it is both a spatial and social ability (Shelton et al., 2012; Clements-Stephens et al., 2013; Tarampi et al., 2016) supported by neural findings (Lambrey et al., 2011; Gunia et al., 2021). Socio-communicational tasks such as referential communication (Keysar et al., 2000; Nilsen and Fecica, 2011; Yadollahi et al., 2022), empathy (Erle and Topolinski, 2015), and Theory of Mind demand the utilization of perspective taking (Barnes-Holmes et al., 2004; Tian et al., 2021; Strikwerda-Brown et al., 2022). Studies with developmentally atypical individuals are in line with the social component of perspective taking since children with autism spectrum disorder experience difficulty in visuospatial perspective taking tasks, while their mental rotation skill is intact (Hamilton et al., 2009; Pearson et al., 2013; Cardillo et al., 2020). There may indeed be a connection between perspective taking capacity and STEAM achievement, even though the link is not studied much (Mix and Cheng, 2012; Newcombe, 2017).

4.1. Mental rotation

Intrinsic-dynamic skills include rotating, folding, slicing, bending, or any other manipulation of the mental representation of an object (Shepard and Cooper, 1982; Resnick and Shipley, 2013; Baykal et al., 2018). Among these various transformations, *mental rotation* is the prototypical spatial representation (Mix and Cheng, 2012; Frick et al., 2013a; Bruce and Hawes, 2014). This skill is often measured by presenting participants with shapes that have been oriented and rotated at different angles and asking them to identify the target shapes (Shepard and Metzler, 1971; Neuburger et al., 2012; Frick et al., 2013b). This type of mental transformation has been called a "rigid transformation" because no matter how an object is rotated, it will maintain its initial properties, such as the distance between any of its two corners (Atit et al., 2013; Resnick and Shipley, 2013; Harris et al., 2013a).

The capacity to process abstract stimuli is the common mechanism between the well-developed mental rotation skill and higher achievement in the STEAM fields. For instance, students or professionals who engage in chemistry need to comprehend the three-dimensional structures of the molecules from various angles, which is a pretty similar task to mental rotation (Hinze et al., 2013; Resnick and Shipley, 2013; Uttal et al., 2013b). Additionally, tasks in mathematics require similar representations with mental rotation, such as moving or manipulating operants (Cheng and Mix, 2013; Tosto et al., 2014; Pirrone et al., 2015), and in geometry, students or professionals need to be able to reason about form and angle of the shapes, just like in the mental rotation tasks (Kinach, 2012; Mix and Cheng, 2012; Bruce and Hawes, 2014). Hence, there is a strong link between performance in STEAM fields and mental rotation tasks (Wai et al., 2009; Uttal et al., 2013a; Hawes et al., 2019).

Moreover, studies suggest that mental rotation skill can be improved (Sorby, 2009; Cheng and Mix, 2013; Kornkasem and Black, 2015). The value of mental rotation concerning STEAM success, combined with the proposal that it is malleable, signifies a need to research its training methods (Caldera et al., 1999; Toub et al., 2019). A meta-analysis by Uttal et al. (2013a) reveals various methods for improving spatial cognition. One of those methods is to reproduce a vast amount of test items from a traditional mental rotation task and to give some items as a training stimulus while giving the rest as testing items (Wright et al., 2008; Meneghetti et al., 2015; Contreras et al., 2018). This method has the theoretical power to demonstrate that spatial cognition is malleable; however, it receives several criticisms. First, it is not an ecologically valid training because individuals do not face similar spatial problems in daily life (Morganti et al., 2009). Second, it is not a proper way to apply in a practical setting such as school when the goal is actually to improve those skills since the task is exhausting and time-consuming, especially for children (Geurts et al., 2014; Newcombe, 2017).

Playing with construction toys, however, is an exceptional method of enhancing spatial skills by engaging in daily routines. More time spent playing with construction toys such as LEGO®'s, Mega Bloks, etc., positively correlates with higher scores in spatial tasks, even when controlling for general cognitive abilities (Jirout and Newcombe, 2015). Assembling construction toys stimulates the exploration of different object positionings in space; consequently, they provide an opportunity to practice mental rotation (Casey et al., 2008; Pirrone et al., 2015; Polinsky et al., 2022). Furthermore, those toys are made from units, and as children build various compositions with them, they create complete mental representations of the units. In the next section, a couple of toy examples that foster mental rotation will be introduced.

4.2. Toy examples for enhancing mental rotation

4.2.1. Traditional toys

LEGO-type building blocks are vastly known for contributing to development of mental rotation skills. Their key affordance is the modularity of the construction units to reassemble multiple times (Brosnan, 1998). In this way, they aid in exploring various configurations in a defined space. Indeed, several toy designs may facilitate mental rotation skills apart from LEGO®. Each of these toys has similar modular systems that signify how and in which direction the construction play should be structured, yet affordances vary based on their elements' shape, scope, and scale (see Appendix A). Despite their differences, with all the toys, the play interaction requires the key action of assembling within two planes, in the x-axis or y-axis, which creates a rigid transformation during the play experience (Atit et al., 2013; Resnick and Shipley, 2013; Harris et al., 2013a).

Toys like Unit Blocks, Montessori Wooden Blocks, Lincoln Logs, Bristle Blocks, KÜP-TAK, Jeujura Wooden Construction Toy, Learning Resources City Engineering, Tangram, and Katamino are a few of the many to highlight within this category (see Figures 1, 2). Those toys are chosen based on market research within established online shopping websites (e.g., Amazon, eBay, etc.). The keywords "construction toy, building block, manipulatives" were used during the market search phase. All these toys can be played by hand and carried around, allowing users to transform their configurations easily. Even though each toy varies regarding the narrative or the form it embodies, they can be grouped together based on their similar affordances (see Appendix A). Unit Blocks, Montessori Wooden Blocks, and Lincoln Logs are composed of primitive-shaped units, and the flat surfaces on each side indicate that units can be stacked on top of each other. Compared to previously introduced toys, one distinct feature of these toys is that they do not have a joint system to assemble pieces together. As a result, the play activity is impacted since, without a joint mechanism, the durability of the structure's core will be limited, and pursuing taller structures is not feasible. Therefore, each piece can only be rotated or stacked while building. Subsequently, toys like Learning Resources City Engineering and Jeujura Wooden Construction Toy deliver real-life narratives like building a chalet and a construction site. Another key aspect of Learning Resources City Engineering and Jeujura

FIGURE 1
Toy examples to foster mental rotation (left to right; Unit Blocks, Lincoln Logs, Bristle Block).

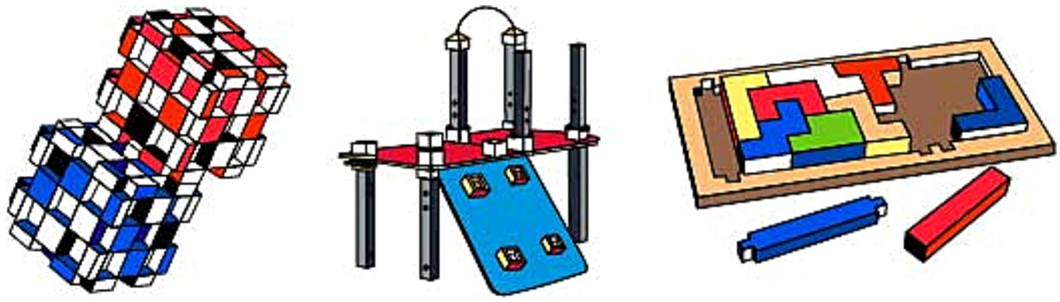


FIGURE 2
Toy examples to foster mental rotation cont (left to right; KüpTak, Learning Resources City Engineering, Katamino).

Wooden Construction Toy is that they possess a joint mechanism on the edges of their modular pieces, providing more balanced and durable structures to be built. Bristle Blocks and KÜP-TAK also embody a joint mechanism, while their grips and holes coat each surface of their modular shapes, allowing an increased variability of shape formations. Last, traditional toys like Tangram and Katamino only enable users to play with configurations of objects on a designated two-dimensional surface. Because of this limitation, while the user can alter the placement of each module by rotating, they cannot build additional levels, which limits the expansion of the play experience.

4.2.2. Digital tools

Moreover, with the rapid increase in technological toys (Ho et al., 2017; Gözüm and Kandır, 2021; Hall et al., 2022), electronic alternatives for spatial play find a considerable market. For example, Tangible User Interfaces (TUIs), which refer to technologically augmented physical entities (Pires et al., 2019), are studied in design literature due to their potential to support the enhancement of spatial cognition (Baykal et al., 2018), alongside traditional (non-electronic) toys (Zosh et al., 2015; Healey and Mendelsohn, 2018; Hassinger-Das et al., 2021). The most salient benefit of digital tools in spatial skill development is to provide affordances for exploring and formulating spatial representations beyond the direct experience. They enable users to expand their spatial thinking to the digital medium (Pires et al., 2019). Boda Blocks, Algobrix, and Pixio are some examples to review in addition to traditional toys (see Figure 3). Boda Blocks is an experimental TUI created by Buechley and Eisenberg (2007), made up of 16 cubes that light up to be green or blue and that can be arranged in different configurations. Some connectors can be attached to any of the six sides of a cube and can be used to tie the cubes to each other. Only one connector can be attached to each surface. The software accompanying the blocks program displays various dynamic three-dimensional light and color patterns, enabling users to experience spatial features multimodally (Buechley and Eisenberg, 2007). Algobrix is compatible with LEGO® pieces thanks to their similarity in size and affordances. Additionally, the toy enables users to turn their constructions into robots by coding to perform various actions. Last, Pixio comprises 8x8x8 mm magnetic cubes that can be attached on all sides, allowing the creation of abstract shapes, animals, buildings, etc. Its small size makes the units easy to manipulate by hand. Pixio's unique feature is its expansion to the digital medium through a mobile application scanning the constructions. In this way, the toy provides opportunities for viewing, manipulating, and moving in virtual space, altering numerous physical and digital structures.

4.3. Mental folding

Neurological evidence supports that mental rotation and mental folding are distinct (Milivojevic et al., 2003; Harris et al., 2013a), but related skills (Hilton et al., 2022) under the intrinsic dynamic category of spatial cognition. When the mental representation of a shape is folded, unlike in mental rotation, properties of the shape change (Resnick and Shipley, 2013; Hodgkiss et al., 2018; Toub et al., 2019),

FIGURE 3
Tangible user interface examples to foster mental rotation (left to right; Boda Blocks, AlgoBrix, Pixio).

and an infinite number of new shapes and objects can be created depending on where or how many times the original shape is folded (Atit et al., 2013; Megahed, 2017). These characteristics make mental folding a non-rigid transformation (Taylor and Hutton, 2013; Harris et al., 2013a; Ormand et al., 2014) and potentially a more challenging representation than rigid ones (Harris et al., 2013b; Angerer and Schreiber, 2019; Hilton et al., 2022).

Mental folding allows one to transform a two-dimensional form into a three-dimensional one, while mental rotation can not practice this representation since it is a rigid mental transformation process (Atit et al., 2013; Hinze et al., 2013; Harris et al., 2013b). Mental folding also significantly contributes to STEAM success (Burte et al., 2017; Hodgkiss et al., 2018; Toub et al., 2019); indeed, a number of studies advocate that mental folding skills may be even more beneficial than mental rotation skills in supporting spatial cognitive development (Taylor and Hutton, 2013; Harris et al., 2013a; Hodgkiss et al., 2018). However, the literature lacks training studies on mental folding. Existing studies tackle training in mental folding through origami, the Japanese art of paper folding, since origami leads individuals to explore forms of various three-dimensional structures (Tenbrink and Taylor, 2015; Megahed, 2017; Wu and Sun, 2020). On the other hand, various toy designs in the market share particular affordances with the paper folding activity, and consequently, they may also improve spatial reasoning. For example, toys can aid the mental folding skill set when implemented in non-rigid assembly systems (Atit et al., 2013; Taylor and Hutton, 2013), allowing the construction of an endless number of geometries and transformation from two-dimensional forms to three-dimensional forms (Kudrowitz and Wallace, 2010; Rigo et al., 2016; Münzer et al., 2018). We suggest that these affordances must be implemented in construction toys more often (design recommendation 1). The following section will exemplify some toys that may enhance mental folding skill.

4.4. Toy examples for enhancing mental folding

Prototypical building blocks have several weaknesses in improving multiple aspects of spatial cognition. Many of the construction toy units in that group are inspired by the shape of a brick such as LEGO® and Mega Bloks. These toys' three-dimensional volume of cubic geometries is divided into two-dimensional standard reference planes within vertical or horizontal axes. This causes the toys to be played with only by focusing on one surface of the object at a time (i.e., creating a tower by placing the pieces on top of each other or creating a wall by placing them side by side) (Reifel, 1984; Rode and Cucuiat, 2018; Polinsky et al., 2022). Due to the cubic form of the pieces, the construction units of LEGO®, Mega Bloks, etc., (see Figure 4) offer a rigid transformation during the play experience (Atit et al., 2013; Resnick and Shipley, 2013; Harris et al., 2013a), and these toys' contribution to spatial reasoning is limited to mental rotation skill.

On the other hand, practicing mental folding skills requires a non-rigid transformation during play experience by producing alternative geometries to cubicle configurations. Besides that, transforming initial two-dimensional physical properties and mental representations of objects into three-dimensional ones is necessary for improving mental folding skill (Hilton et al., 2022). Various toy designs have these features, such as ZozoPlay, Magna-Tiles, GeoMag, and Squigz Fat Brain Toys (see Figures 4, 5). Pieces of ZozoPlay are made of pipe-like modular shapes that come in different forms. Each unit has one small and one wide end to indicate the joint mechanism embedded within the design. Magna Tiles are made of flat, primitive-shaped, modular plates with magnetic fields around their edges to assemble pieces. Additionally, GeoMag consists of two main elements: spikes and balls. Spikes are short, flat bars with magnetic fields on their ends to signify where the ball can be assembled. The ball is, on its own, a magnetic ball that can be easily attached to other pieces. Furthermore, toys like Squigz Fat Brain Toys have an assembly system that holds each piece together without benefitting from the magnetic field. Squigz Fat Brain Toys utilize a vacuum to attach pieces together as the joint system. All the pieces in the previously presented toys are small, so they can be easily manipulated, carried around, and played with. In this group of toys, the play experience usually starts with constructing two-dimensional primitive closed geometries. The activity will be transformed into three-dimensional geometries by adding pieces to the z-axis with a certain angle or bending the shape from a particular edge. There are endless combinations the pieces can attach to since the joint mechanisms enable users to compose undefined shapes and geometric structures. Thanks to these non-rigid transformations, users can mentally visualize the manipulation they will apply, then transform the object from two-dimensional to three-dimensional, which may utilize mental folding capabilities in return. Lastly, since all the folding activities require a certain angle of rotation (Hilton et al., 2022), these toys may enhance both mental rotation and mental folding skills at the same time.

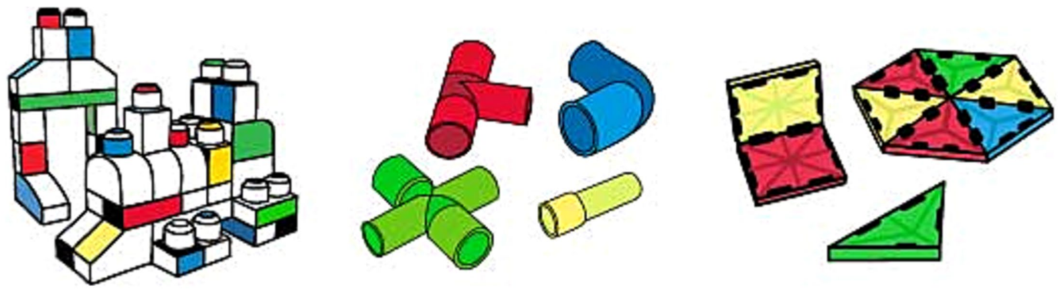


FIGURE 4
Toy examples to foster mental rotation (Mega Bloks on the left) and mental folding (middle to right; ZoZoplay & Magna Tiles).

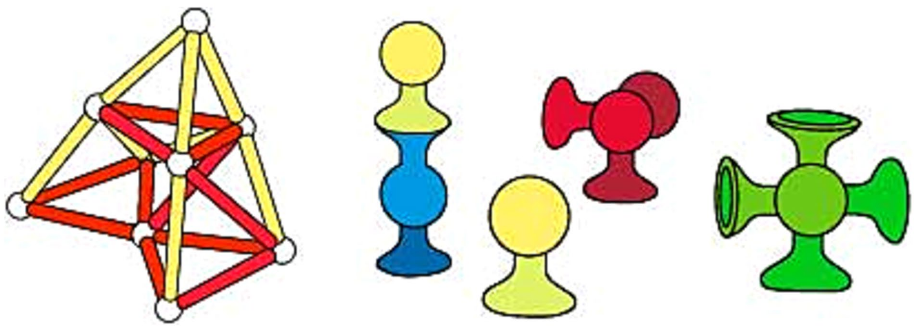


FIGURE 5
Toy examples to foster mental folding cont. (left to right; GeoMag & Squigz Fat Brain Toys).

4.5. Perspective taking

Like mental folding, training of the extrinsic-dynamic elements of spatial cognition, dubbed as perspective taking skill, also requires more attention given that its social aspects receive more focus than its spatial characteristics. Indeed, in the literature, it is acknowledged that perspective taking skills can be divided into subgroups: visual perspective taking (understanding how a scene looks from another frame of reference), affective perspective taking (an individual's ability to understand that others may feel different emotions than oneself), cognitive perspective taking (individual's ability to reason about other people's thoughts) (Kurdek and Rodgon, 1975; Newcombe, 1989; Yadollahi et al., 2022). Cognitive perspective taking skills form the basis of the Theory of Mind (Selman, 1980; Barnes-Holmes et al., 2004; Apperly, 2012), and affective perspective taking forms the basis of empathy (Ruby and Decety, 2004; Lamm et al., 2007; Erle and Topolinski, 2015). Among these categories, researchers focus on enhancing cognitive perspective taking skills the most. There are many interventions for cognitive perspective taking, and a few for affective perspective taking; yet, there are lack intervention studies with children that are devoted to visual perspective taking skill (Uttal et al., 2013b; Mori and Cigala, 2015; Vander Heyden et al., 2017). A recent study by Tian et al. (2021) employs a visual perspective taking training. However, this study's initial aim is not to enhance visual perspective taking; rather, they investigate the link between the Theory of Mind and spatial skills. The spatial cognition training with construction toys supports the direction of the causal relationship such that improvement in spatial cognition leads to an improvement in the Theory of Mind performance, owing to the mediatory mechanism of perspective taking (Tian et al., 2021). A potential explanation for the shared mechanism between the Theory of Mind ability and spatial cognition can be the traditional Level 1 & Level 2 perspective taking framework proposed by Flavell (1974). In this model, two levels of visual perspective taking are defined: Level 1 refers to the understanding that other individuals may have a different line of sight and the ability to determine what others can and cannot see, while Level 2 perspective taking is the understanding that others may see things differently, and the ability to determine the positions of objects from the other's point of view (Flavell, 1974; Kessler and Wang, 2012; Frick et al., 2014).

A classical referential communication task created by Keysar et al. (2000) also demonstrates the importance of the perspective taking skill in a social communicational setting. Researchers provided participants with a shelf with 16 slots; some slots had an item within, and some were empty. All the items are visible from the addressee's (the participant's) view, but some are blocked from the vision of the director (a research assistant) sitting on the other side of the shelves. The participant's task is to rearrange the shelves with the instructions of the director. For example, there are three candles on the shelves: a small candle, a medium candle, and a big candle. However, the small candle is blocked from the director's perspective; s/he can only see the medium-sized candle and the big candle. When the director asks the addressee to move the small candle, s/he must take the director's perspective and determine that s/he must be referring to the medium size candle, as the smallest one is blocked from his/her view. This is a visual perspective taking task, and it also demonstrates perspective taking skill's communicational role to establish common ground between the addressee and the director (Keysar et al., 2000; Nilsen and Fecica, 2011; Kessler and Wang, 2012).

4.6. Toy examples for enhancing perspective taking

Both social and spatial aspects of the play experience can be enhanced within an informal family setting by altering and referring to various configurations of the toys enabling manipulation. Yet, current toy designs usually use the brick system as the construction unit. Bricks are usually quite small, and as it is mentioned in the previous sections, their only affordance allows construction in the x and y axes (Reifel, 1984; Rigo et al., 2016; Rode and Cucuiat, 2018); consequently, much of the space exploration will be disregarded during play. This problem can be overcome by expanding the size of the units and adding joint mechanisms that afford to construct alternative geometries such as spherical ones (design recommendation 2), since large-scale units and spherical geometries enable individuals to expand their use of space and move between objects, which require exercise of the extrinsic-dynamic spatial cognition (Sas and Mohd Noor, 2009; Münzer et al., 2018; Cardillo et al., 2020).

Strawctures (Yu et al., 2022) and Stocs may provide previously mentioned affordances to practice perspective taking (see Figure 6). Strawctures consist of pipes and wheel-like stabilizers for the corners. Stocs are simply consolidated ropes that can create outline structures such as a tent or a boat by knotting. These toys provide an alternative to the linear motion field by creating different three-dimensional shapes, such as spherical geometries, owing to the assembly system of units allowing to join them in various angles and combinations. The advantage created by spherical geometries is that the toy encourages movement in a larger volume in the three-dimensional space, and the modularity of the design allows the shape to be as large as the player desires. For these reasons, it can be said that designs enabling spherical geometry may be more amenable to exercising perspective taking (design recommendation 2).

Another way to enhance perspective taking skills is to establish an interaction within the larger volume by increasing the size of construction units. Blockspot® is an example of a construction toy that consists of large units (see Figure 6), triggering the user to walk around the compositions and use the play space holistically (Cohen and Emmons, 2016), thus encouraging the use of extrinsic spatial cognition. Another candidate for enhancing perspective taking skill is Gigi Blocks, which consists of large cardboard blocks with tabs on the top and gaps underneath, similar to the LEGO® 's brick system, aside from the size (see Figure 7). These cardboard bricks can be stacked on top of each other to build real size structures. Moreover, Imagination Playground is a large-scale construction set made of foam blocks, some circular, some cubic, etc., modeled after archetypal playground elements encouraging children to build their own playground (see Figure 7). The modules can be stacked on top of each other or attached using connectors that fit into the holes in the building blocks. Since the sizes of the blocks are large, children can walk through their compositions and experience their building as a whole. Lastly, The Toy is a large-scale construction set made of fiberglass sticks and 30-inch triangle and square panels made of vinyl (see Figure 7). It can compose anything from tents to houses to tunnels (Ginoulhiac, 2013). While each toy offers different play opportunities based on its affordances, they all encourage its users to take different points of view while interacting and building with the toy, positively impacting perspective taking skills.

Mental rotation, mental folding, and perspective taking skills were presented among the physical properties of construction toys. On the other hand, these toys offer affordances beyond physicality. A construction play experience elicits verbal, gesture, and narrative interaction, which also contribute to spatial mental representations. Construction toys' interactional affordances, which invite fruitful play interaction in spatial cognition development, will be discussed in the next section.

5. Features of construction toys to facilitate play experience

Designing play interactions is as important as designing the physical properties of the toys (Wooldridge and Shapka, 2012; Black et al., 2016; Yamada-Rice, 2018) (design recommendation 3). For instance, one of the major strengths of construction toys is to promote spatial talk during play sessions (Ferrara et al., 2011; Levine et al., 2012; Yang and Pan, 2021) and various toys tend to elicit spatial language in different amounts (Verdine et al., 2014). There is a link between spatial language use and improvement in mental rotation skill (Polinsky et al., 2017; Ralph et al., 2020; Turan et al., 2021). The

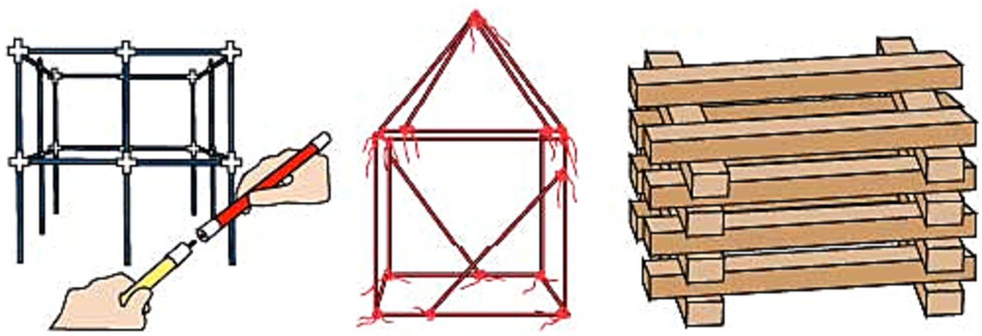


FIGURE 6
Toy examples to foster perspective taking (left to right; Strawctures, Stocks, Blockspot®).

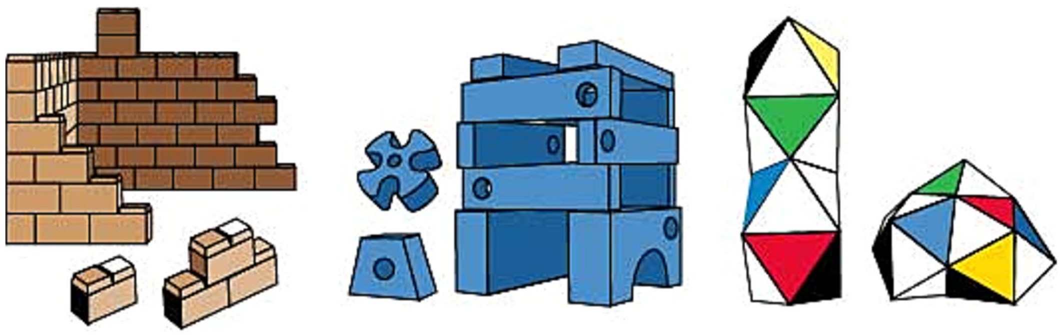


FIGURE 7
Toy examples to foster perspective taking cont (left to right; Gigi Blocks, Imagination Playground, The Toy).

language used during construction play enables one to create and express mental representations, and triggers spatial thinking (Casasola et al., 2020; Bower et al., 2020a; Miller-Goldwater and Simmering, 2022). Designing play experience is as important as designing the toys' objecthood in the toy design process (Wooldridge and Shapka, 2012; Verdine et al., 2014; Black et al., 2016). Play experience entails all the communicative interactions children experience around the toy, including with their parents, teachers, peers, etc. when they play collaboratively (Healey and Mendelsohn, 2018; Ralph et al., 2020). This is also relevant for spatial play since it elicits spatial language (Ho et al., 2017; Verdine et al., 2019; Casasola et al., 2020). According to the coding scheme proposed by Cannon et al. (2007), spatial language can be captured through words describing spatial features (e.g., near, in front of, next to, tilt it down, etc.) and properties of objects (e.g., big, short, square, round, etc.). It has been shown that parents use more spatial language when playing with blocks (Ferrara et al., 2011) and puzzles (Levine et al., 2012), and when parents use more spatial language, children's usage increases as well (Pruden et al., 2011; Kısa et al., 2018; Clingan-Siverly et al., 2021).

Enabling guided play scenarios, where spatial language is encouraged, is an opportunity for implementing linguistic input into play. In guided play, adults focus the child's interest on the learning objectives by using verbal scaffolding, asking open-ended questions, posing problems, thinking out loud, praising and encouraging discoveries made by the child (Fisher et al., 2013; Weisberg et al., 2013; Cohen and Emmons, 2016). It has been demonstrated in multiple studies that children benefit from guided play more than they do from free play or didactic play in terms of learning new skills, including mental rotation (Fisher et al., 2013; Ramani et al., 2014; Borriello and Liben, 2017).

Furthermore, guided play with construction toys can be an engaging way of improving spatial cognition for adults and children simultaneously. However, to our knowledge, no studies investigated the mutual benefits of guided play for adults and children. Studies assert that spatial skill malleability does not exclude adults (Uttal et al., 2013a; Cherney et al., 2014; Kornkasem and Black, 2015). Adults may also benefit from interacting with the right instrument designed to enhance spatial skills; however, the literature lacks an engaging way to develop adult spatial cognition (Newcombe, 2017). Guided building play can improve adults' spatial skills, as it helps to improve children's, since adults also enjoy interacting with construction toys (Ginoulhiac, 2013; Toub et al., 2019). Previous literature implies that spatial gains may be simultaneous for parents and children dyads engaging in spatial play, no particular study sheds light on this subject.

In terms of the content of the guided play, presenting a training stimulus in combination with either realistic or fantastic but especially with fantastic narrative context is found to be beneficial for learning in many domains, for instance, word learning (Weisberg et al., 2015). The same is also valid for spatial cognition, such that the benefit a child gains from the language produced during play can be enhanced by adding a narrative component (Rohlfing and Nachtigäller, 2016), since the narrative may motivate the children and make the play experience more engaging (Casey et al., 2008). In addition to helping with the learning process, narrative input is known to help retain what is learned (Bower and Clark, 1969; Graesser et al., 1980). Thus, implementing thematic elements such as animals or human characters into the construction toy can lead children to create stories, engage more enthusiastically with the enacted story world, and interact more in a spatial manner.

However, it must be noted that the thematic pieces should be supplementary material rather than the main focus as they may distract the child and jeopardize the spatial characteristics of the play activity (Stanton and Weisberg, 1996; Wellhousen and Kieff, 2001; Tunks, 2009). To compose an architectural setting once and create stories inside the structure, such as a doll house, is not an efficient way of practicing spatial skills because building and rebuilding multiple times is the key parameter for practicing spatial representations (Jirout and Newcombe, 2015; Fanning, 2018; Rode and Cucuiat, 2018). The aforementioned disadvantageous thematic elements can be observed in the themed sets based on objects, vehicles, and buildings from media such as Star Wars, Harry Potter, Lord of the Rings, etc. These product lines act more as collection items than construction toys (Wolf, 2014; Fanning, 2018). Once individuals get these sets, they follow the instructions, complete the suggested composition and rarely pull it apart again. In this way, the construction pieces become display material and lose their ability to promote spatial thinking when built only once. Another side effect of the thematic product lines is that the benefit of stimulating creativity would be lost when predetermined instructions are followed instead of free construction (Moreau and Engeset, 2016; Fulcher and Hayes, 2017; Rode and Cucuiat, 2018).

Although this issue is mostly considered in relation to children's spatial learning and play experience, it is worth noting that adults' spatial gains also suffer from construction toys that are overwhelmingly themed. Construction materials targeting adults are almost exclusively of this sort and lack the assembling and reassembling aspects that promote spatial learning. As previously mentioned, adults can benefit from spatial training either by themselves or engaging in guided play (Newcombe et al., 2013; Cherney et al., 2014; Kornkasem and Black, 2015). Through a convenient design that engages both the adult and the child, construction toys can eliminate the age gap in the market and bring adults and children together in a way that creates an opportunity for mutual benefit gathered from a single training tool.

Gesture production is another scaffolding tool children can benefit from while playing with construction toys, especially if they are designed to encourage both the child and the adult to produce gestures (Kısa et al., 2018; Bower et al., 2020b; Clingan-Siverly et al., 2021). Both gesture production and observing someone while gesturing are valuable for fostering spatial reasoning (Ehrlich et al., 2006; Chu and Kita, 2011; Toub et al., 2019). Besides, Goldin-Meadow et al. (2012) revealed that gesture production is more effective for mental rotation improvement than observing someone while gesturing. Gestures' contribution to mental rotation skill is rooted in the communicating visuospatial modality (Baykal et al., 2018; Yang et al., 2020). For instance, gestures can represent objects, directions, and orientations (Alibali, 2005; Galati et al., 2017; Karadöller et al., 2021); they essentially allow spatial language to be converted to physical expressions. Indeed, gestures are situated in the middle of the visual and verbal expression styles (Newcombe et al., 2013). In an empirical study, Stieff et al. (2016) demonstrated that gestures foster STEAM performance by converting the imagined movement of mental representations into a concrete movement in the physical space. In this way, gestures provide solutions for the spatial visualization challenges, which can be encountered in STEAM tasks (Chu and Kita, 2011; Stieff et al., 2016). It is also found that worse performers in the traditional paper and pencil mental rotation task tend to gesture more to convey static information in comparison to those who performed better in mental rotation (Göksun et al., 2013), demonstrating that individuals strive to resolve a cognitively demanding spatial task for them through the aid of gestures and overcome the challenge. Using gestures during spatial activities can facilitate spatial skills; however, few studies investigate the role of gesture input in spatial reasoning (Yang et al., 2020; Clingan-Siverly et al., 2021).

To sum up, the interactions that engage adults with their children can provide opportunities for both parties to benefit since studies demonstrate that adult spatial cognition is also malleable (Uttal et al., 2013a; Cherney et al., 2014; Kornkasem and Black, 2015) and adults also enjoy playing with construction toys (Ginoulhiac, 2013; Toub et al., 2019), although there is no inclusive, enjoyable intervention for their spatial skills (Newcombe, 2017). Therefore, concept designs that invite children and adults to play and benefit together must be produced (design recommendation 4). To date, no research has investigated the simultaneous cognitive benefits of construction play for adults and children. Still, there are studies showing adults scaffold children's spatial development (Vygotsky, 1978; Trawick-Smith, 1998) by using narratives (Casey et al., 2008), spatial language (Ferrara et al., 2011; Pruden et al., 2011; Cohen and Emmons, 2016), and gestures (Chu and Kita, 2011; Kısa et al., 2018; Clingan-Siverly et al., 2021). Features of language, narrative, and gesture input must be incorporated into the play experiences (Verdine et al., 2014) to facilitate at-home STEAM development (design recommendation 5). Furthermore, affordances provided by the construction toys must be varied with the choice of more abstract units to build unlimited combinations (Reifel, 1984; Ginoulhiac, 2013; Trawick-Smith et al., 2014) as opposed to contemporary licensed thematic sets, in which individuals consistently replicate the forms of popular movie settings (Wolf, 2014; Fanning, 2018) and create display materials in which narrative features shadow the construction play (design recommendation 6).

6. Discussion and conclusion

Access to quality STEAM education starting from the preschool period is known to be a predictor for future academic success (Gözüm et al., 2022). Thus, play interactions are fruitful investments for joyfully and effectively increasing STEAM success in an informal context, in view of strong evidence for the link between well-developed spatial cognition and achievement in the STEAM-related fields. A multitude of studies demonstrate that playing with construction toys enhances spatial reasoning; thus, making construction toys an accessible tool contributes to informal STEAM development. Although certain aspects of spatial skills in relation to construction toys have been already investigated, this paper pointed out several gaps in the research area. To bridge this gap, it revisited developmental psychology and design literature, presented existing discussions in the developmental psychology field and some construction toy examples available in the toy market and design studies through a benchmark. In the end, six recommendations were identified to provide guidance about what could be done further to support both toy design and developmental psychology by strengthening the link between the two fields.

One of the main takeaways of this paper is that developmental psychology and design fields should collaborate more to design toys that contribute to informal STEAM development in children. Design researchers have an important role in this regard as they can act as the mediators of theoretical knowledge derived from developmental psychology, who turn empirical knowledge into actionable design guidelines for design practitioners. The first research question in this paper was which findings from developmental psychology had not yet been applied to toy design. In search of an answer, we created a benchmark for construction toys' potential contributions to spatial skills, which is prepared in accordance with spatial affordances of over fifty toys from the market and design research studies (see Table 2 for the spatial skill contribution of the toys, and Appendix A for the toys' relevant affordances). A thorough review of these toys demonstrated that existing construction toys focus more on supporting mental rotation skill, while very few address mental folding and perspective taking skills. This seems to be a missed opportunity for design, indicating a need to integrate design features that can support various spatial cognition skills (i.e., mental folding and/or perspective taking in addition to mental rotation). The benchmark showed that the main problem in this literature is the need to investigate other construction units in addition to the typical brick system in spatial toys. Accordingly, there are very few toy options that can foster perspective taking and all three skills together, although various toy designs may contribute to different spatial skills. Studies conducted with these toys are limited to small-scale user studies. Empirical methodology with larger sample sizes comparing different toys' affordances as stimuli can provide evidence regarding the positive impact of toys on the three spatial skills (i.e., mental rotation, mental folding, and perspective taking).

The second research question was how to present the knowledge obtained regarding the first question to designers in a feasible way while effectively closing the gap between the two disciplines. In order to do so, the findings from theoretical foundations of developmental psychology were combined with the design features of the construction toys to demonstrate market tendencies for enhancing spatial skills (see Table 2). Additionally, we produced six design recommendations that designers can refer to while developing new toys (see Table 3). These recommendations include some key points for the toy design as well as designing the play experiences, since designing a play interaction is as important as the physical features of the construction toys. If training spatial skills in young children will be achieved, their adult partners (parents, teachers, etc.) must be encouraged to produce the necessary spatial input (e.g., spatial talk or gesture) for the emergence of spatial play. Another potential contribution of engaging adults in spatial play is that they may also benefit from this interaction in the form of spatial skills development. Thus, the interests of different personas (i.e., adults and children) should be considered. In line with these insights and background literature, the design recommendations were prepared to inspire designers and fill the gaps in this area of literature.

The final research question was what are the responsibilities that developmental psychologists had in bridging the gap between their field and toy design. On the side of developmental psychology, there is a call for more research of construction toy designs that include different affordances rather than focusing solely on typical brick-shaped units (see Appendix A). Doing so would potentially provide empirical evidence of the expected benefits of a wider range of construction toys to mental folding and perspective taking skills, skills that are overlooked, in addition to the well-studied mental rotation skills. The benchmark provided in Table 2 attempts to give a glimpse of the full picture in the construction toy market based on their potential contribution to mental rotation, mental folding and

TABLE 2 Benchmark for the construction toys' potential contribution to spatial skills.

	Mental rotation	Mental rotation and mental folding	Mental rotation and perspective taking	Perspective taking	Mental rotation and mental folding and perspective taking
	LEGO (Wolfgang et al., 2003; Wolf, 2014)	Brainflakes	Rigamajig	Tommy Blocks (Rigo et al., 2016)	Zometool
	Mega Bloks	Learning Resources Gears! Gears! Gears!	Imagination Playground (Ginoulhiac, 2013)	Sifteo (Geurts et al., 2014)	Polydron
	Unit Blocks	Squigz Fat Brain Toys	gigi Blocks	Co-gnito (Panagiotidou et al., 2022)	MagnaTiles (Ralph et al., 2020)
	Montessori Wooden Blocks (Baykal et al., 2018)	Topobo (Raffle et al., 2004; Parkes et al., 2008)	Habitadule		GeoMag
	KÜP-TAK	Posey (Weller et al., 2008)			Strawctures (Yu et al., 2022)
	Lincoln Logs (Ginoulhiac, 2013)	Kinematics (Oschuetz et al., 2010)			Stocs (Vander Heyden et al., 2017)
	Jeujura Wooden Construction Toy	ZoZoplay			K'Nex
	Bristle block	Vkoizzi			Geemo (Ginoulhiac, 2013)
	Learning Resources City Engineering	Plus-Plus			DIY Model Doll House
	Fischertechnik	Tinkertoy (Baykal et al., 2018)			Marble Maze (Vander Heyden et al., 2017)
	Kunmark (drill toy)	Toyi (Agirbas et al., 2022)			The Toy (Ginoulhiac, 2013)
	Pontiki	Clixo			
	Jigsaw Puzzle (Levine et al., 2012)	Wikki Stix (Baykal et al., 2018)			
	Tangram (Baykal et al., 2018)	Wacky Tracks			
	Katamino	Pop Tubes			
	Q.Bitz	Speks Flex			
	Boda Blocks (Buechley and Eisenberg, 2007)	Legoon (Yang and Druga, 2019)			
	AlgoBrix				
	Pixio				
Total:	19	17	4	3	11

TABLE 3 Recommendations for toy designers.

1. Include mental folding components in toys, as mental folding also has value for STEAM success (Harris et al., 2013a; Resnick and Shipley, 2013; Taylor and Hutton, 2013; Burte et al., 2017; Hodgkiss et al., 2018; Toub et al., 2019)
2. Design large-scale or spherical toys to facilitate perspective taking skill, as perspective taking is related to both spatial and social skills (Sas and Mohd Noor, 2009; Shelton et al., 2012; Tarampi et al., 2016; Vander Heyden et al., 2017; Cardillo et al., 2020; Tian et al., 2021)
3. Consider the entire user experience playing during the design process rather than focusing only on the physical properties of the toys (Wooldridge and Shapka, 2012; Weisberg et al., 2013; Black et al., 2016; Healey and Mendelsohn, 2018; Yamada-Rice, 2018; Verdine et al., 2019)
4. Embrace multiple personas, such as parents and children playing together, so both the child and the adult can benefit from enhancing spatial skills (Lin, 2010; Uttal et al., 2013a; Ginoulhiac, 2013; Cherney et al., 2014; Kornkasem and Black, 2015; Borriello and Liben, 2017)
5. Design toys that will elicit spatial language, narrative, and gesture use as much as possible (Casey et al., 2008; Ferrara et al., 2011; Pruden et al., 2011; Verdine et al., 2014; Stieff et al., 2016; Clingan-Siverly et al., 2021)
6. Avoid using themed products that may limit imagination. The narrative must be a complementary feature without shadowing the construction play. Provide users with abstract designs to stimulate symbolic thinking and allow different configurations as an alternative to typical brick systems (Reifel, 1984; Ginoulhiac, 2013; Trawick-Smith et al., 2014; Wolf, 2014; Rigo et al., 2016; Fanning, 2018)

perspective taking skills. However, it should be noted that it is hypothetical to claim whether the affordances of those toys satisfy their matched spatial skills due to the lack of empirical research conducted on such toy designs. Hence, it would be beneficial for future studies to investigate the above-mentioned connections.

Overall, this review aimed to point out that there is a lack of collaboration between developmental psychology and toy design fields. Developmental psychology studies are mostly executed with a limited variety of toys (i.e., block-type construction toys) and are focused on the mental rotation skill. Alternative toy designs are not considered while facilitating spatial development, although their affordances may contribute to different aspects of spatial cognition (i.e., mental folding and perspective taking). On the other hand, toy design research barely considers theoretical frameworks from developmental psychology, or the empirical backgrounds of existing products in the market are not always clear. Through revealing these issues and investigating developmental psychology and toy design with a lens of spatial cognition, this paper initiates a dialog between these fields to foster informal STEAM development.

Author contributions

Çİ, ME, DK, AC, TG, and AK designed and conceptualized the study. Çİ, ME, and DK reviewed the literature and wrote sections. ME and DK conducted market research, drew visuals, and prepared tables. Çİ and DK wrote the first draft of the manuscript. AC, TG, and AK read, revised, and provided feedback for the manuscript. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1137003/full#supplementary-material

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Parents' approaches to numeracy support: what parents do is rarely what they think is most important

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The math children are exposed to at home is a crucial source of early math knowledge, but little is known about parents' general approaches for supporting their children's math development at home. The current study examined what general pedagogical approaches parents believed to be most important to use in their home and if these beliefs aligned with the approaches they reported using most often. In a survey of 344 U.S. preschool parents (56% mothers, 61% sons, 77% White, 79% with a bachelor's degree or more), 83% of parents showed a mismatch in the pedagogical approach they used most often compared to what they believed to be most important to use. The most popular pedagogical approach to use was incorporating math during daily living experiences (the "daily living" approach) compared to three other approaches. Notably, although used most often, the "daily living" approach was the approach most frequently selected as least important. Rather, "direct teaching" was the approach most frequently selected as most important. Overall, this suggests a disconnect between how parents approach their home math support and what they believe is most important for their child's math development at home.

KEYWORDS
home math environment, early math development, pedagogy, parents' beliefs, parent support, involvement

Introduction

Early math knowledge predicts later math achievement, which in turn predicts future academic and life success (Rivera-Batiz, 1992; Duncan et al., 2007; Reyna et al., 2009; Watts et al., 2014). One learning environment important to early math knowledge development is the home math environment (HME). The HME encompasses the math-related activities and interactions children engage in at home, including the math support that parents provide their children through math talk, toys, everyday interactions, and direct instruction. Overall, parents report engaging in home math activities with their preschool children at least once a week (Saxe et al., 1987; Skwarchuk et al., 2014; Sonnenschein et al., 2016; Rittle-Johnson and Zippert, 2018). However, little research has examined parents' pedagogical approaches, or the teaching approaches parents use and believe are important for helping their young children learn math at home. Three studies have examined parents' pedagogical approach beliefs, and some evidence suggests parents differ in these beliefs based on their socioeconomic status (SES). However, there is no agreed-upon measure across studies and no study has examined pedagogical approach use.

The current study examined parents' pedagogical approach beliefs and how they relate to their pedagogical approach use. Parents' beliefs are related to the frequency and complexity of their numeracy support which in turn are related to their child's math knowledge (see Douglas et al., 2021 for a review). For example, parents who believed numeracy skills were important for their child also reported more frequent and advanced numeracy activities compared to parents with lower numeracy expectations (Skwarchuk et al., 2014) and the same was true for parents who rated their child as having better numeracy skills than their peers (Zippert and Ramani, 2017; Uscianowski et al., 2020; Zippert and Rittle-Johnson, 2020). Additionally, numeracy support is positively associated with children's early and later math knowledge (Mutaf-Yıldız et al., 2020; Zhang et al., 2020; Daucourt et al., 2021).

The current study focuses on a rarely studied aspect of parents' beliefs and support: pedagogical approach. Four common pedagogical approaches for supporting math learning have emerged from research with parents in the United States: (1) incorporating math during daily living experiences, or the "daily living" approach, (2) setting time aside to directly teach math skills, or the "direct teaching" approach, (3) providing math-related toys or activities, or the "give math toys" approach, and (4) incorporating math during activities their child enjoys, or the "during child enjoyment" approach (Cannon and Ginsburg, 2008; DeFlorio and Beliakoff, 2015; Sonnenschein et al., 2016). These pedagogical approaches align with some HME literature which attempts to categorize HME activities as informal or indirect and formal or direct (LeFevre et al., 2009; Skwarchuk et al., 2014). Specifically, the "daily living," "give math toys," and "during child enjoyment" approaches align with the common definition of informal or indirect activities (i.e., activities that support children's math learning indirectly, where numeracy is not the purpose of the activity but occurs incidentally). In contrast, the "direct teaching" approach aligns with the definition of formal or direct activities (i.e., activities that support children's learning directly and intentionally to enhance children's numeracy knowledge; Skwarchuk et al., 2014). Understanding how parents use and assign value to these pedagogical approaches could be an important part of HME that has been ignored.

Three previous studies have measured parents' *beliefs* about pedagogical approaches, and results about which approach parents believed to be most important varied across the studies and the SES background of the parents. In a study with U.S. parents from unknown SES backgrounds, parents most frequently described "daily living" or "during child enjoyment" approaches when asked an open-ended question about the best way for their preschool-aged child to learn math at home (Cannon and Ginsburg, 2008). Similarly, in a study with U.S. parents from low and middle-SES backgrounds, as measured by their income-based qualification to attend federally funded or pay for private preschool programs, parents from middle-SES backgrounds most frequently chose the "daily living" approach when asked to rank a list of three approaches in order of importance (DeFlorio and Beliakoff, 2015). In contrast, in the same study, parents from low-SES backgrounds most frequently chose the "direct teaching" approach as most important. Similarly, in a study with U.S. parents from low SES backgrounds only, as measured by income-based qualification to a Head Start Preschool program, parents most frequently described the "direct teaching" approach when asked about the best way to help their child learn to do math (Sonnenschein et al., 2016). Thus, there is some evidence that parents differ in these beliefs based on their SES, with parents from low SES backgrounds believing "direct teaching" is most important and parents from middle or high SES backgrounds believing "during child enjoyment" is most important. One of the studies also reported that some beliefs varied with the child's age, with parents of four-year-olds more likely to believe "give math-related toys" was most important than parents of three-year-olds, while their beliefs about the "daily living" and "direct teaching" approaches did not differ by child age (DeFlorio and Beliakoff, 2015).

Notably, DeFlorio and Beliakoff (2015) first asked parents a question of *use:* "Which of the following approaches do you use at home on a regular basis to help your child develop mathematical knowledge and skills?" However, they seemed to falsely equate belief and use, where anyone who chose more than one approach was asked to rank the approaches in order of importance, which is the question that they reported in their results. The current study aimed to address this question by using DeFlorio and Beliakoff (2015) first question but following up with a question of use, not belief, to examine both beliefs and use, and how parents' pedagogical approach beliefs relate to their pedagogical approach use. The current study examines three questions:

1. What pedagogical approach do parents report using most often to help their child learn math at home? Are there differences by child age, parent education, or income? We hypothesized parents would use one of the more informal approaches (e.g., "daily living," "give math toys," or "during child enjoyment") most often over the more formal approach of "direct teaching" because families engage in informal math activities more often than formal activities at home (Skwarchuk et al., 2014; Rittle-Johnson and Zippert, 2018; Susperreguy et al., 2020). We explored potential differences by parent education and income, two commonly used measures of SES, and potential differences by child age because differences exist for related HME factors (DeFlorio and Beliakoff, 2015; Thompson et al., 2017). Although our age range is narrow and age-related differences are more likely in a wider age range, we still explored potential differences by child age.
2. What approach do parents believe is most important for helping their child learn math at home? Are there differences by child age, parent education, or income? We hypothesized that in our sample of predominantly middle and upper SES parents, "daily living" approaches would be reported as most important on average (Cannon and Ginsburg, 2008; DeFlorio and Beliakoff, 2015). We explored potential differences by parent education and income, two commonly used measures of SES, and potential differences by child age because one study suggests these differences exist (DeFlorio and Beliakoff, 2015). Although our age range is narrow and age-related differences are more likely in a wider age range, we still explored potential differences by child age.
3. Is there a difference between the pedagogical approach(es) parents use most often and believe is most important? We tentatively hypothesized beliefs and use would align as they do when measured in other contexts.

Methods

Participants

Participants were 344 U.S. parents of 3- to 4-year-olds (child mean age = 3 years and 10 months, SD = 7.8 months), with almost as many fathers as mothers responding (44% vs. 56%). More parents of boys than girls responded (61% vs. 39%) and 58% reported that their child was enrolled in preschool the previous year. Most parents reported their race as Caucasian or White (77%). Additionally, 19% of participants identified as Hispanic or Latino. Most parents (72%) reported a household income above $45,000 and 79% had at least a bachelor's degree. See Table 1 for demographic information.

Measures

Pedagogical approach use and belief

The questions, and the first three approaches provided, were adapted from DeFlorio and Beliakoff (2015) in an attempt to create an agreed-upon measure (see Supplementary Table S1). A fourth pedagogical approach, "during child enjoyment," was included based on a common open-ended response from two other studies (Cannon and Ginsburg, 2008; Sonnenschein et al., 2016). The first question asked, "Which of the following approaches do you use at home on a regular basis to help your child develop mathematical knowledge and skills?" (DeFlorio and Beliakoff, 2015). If a parent selected more than one approach, they automatically received a follow-up question "Which approach do you use most often?" All parents were then asked, "Rank the following approaches from least important (1) to most important (4) in your home." (DeFlorio and Beliakoff, 2015). All questions were close-ended and parents were provided four pedagogical approaches (see column 2 in Table 2).

Demographics

Each parent reported their race/ethnicity, gender, and child's age, and child's gender at the end of the survey. They also reported their household income and their highest educational attainment, which we used as two measures of SES for our analyses.

Procedure

Parents were recruited using CloudResearch, an internet-based research platform that integrates with Amazon's crowdsourcing platform Mechanical Turk (MTurk; Litman et al., 2017). Our initial goal was to recruit based on education with a goal of recruiting a representative sample of the United States, but initial participation was low, specifically because we had other requirements. In the end, to achieve a powerful enough sample size, we had to change our requirement to not target participants based on education. Participants were prescreened in a survey requiring them to be in the United States, have a 95% approval rate from their previous MTurk participation, and be parents, and the prescreening survey asked about their child's age. Qualifying parents of 4- and 5-year-olds were able to complete the survey for the current study. Parents were paid $0.05 for the initial screening survey and $10 for completion of the study. After providing informed consent, parents completed surveys on their pedagogical approach use and beliefs and their demographics. Parents completed attention checks that were embedded in the survey such as "To show that you are paying attention, please select the 'none of the above' option as your answer." Participants who failed at least one attention check ($n = 121$) were not included in the final sample of 344 participants.

Results

Pedagogical approach use

Each approach was used by 52–73% of parents and most parents (88%) reported using more than one pedagogical approach. Table 2 shows descriptive statistics for the pedagogical approach questions. The "daily living" approach was most frequently selected as the approach they used most often. The "during child enjoyment" approach was least frequently selected. A chi-square difference test indicated no significant difference in parents' pedagogical approach used most often by child age as a categorical variable in years, X^2 (3, 332) = 7.06, $p = 0.07$ or continuous variable in months [X^2 (102, 233) = 91.14, $p = 0.77$]. See S2 for descriptive statistics by child age.

TABLE 1 Demographic statistics.

Variable	Proportion	Variable	Proportion
Child Age		**Household income**	
3 year old	0.52	Less than $27,000	0.07
4 year old	0.48	$27,000 to $44,999	0.20
Race/Ethnicity		$45,000 to $89,999	0.41
White	0.77	$90,000 to $134,999	0.25
Black	0.08	$135,000 or more	0.06
Asian or Pacific Islander	0.05	**Highest educational attainment**	
Biracial or Mixed Race	0.04	High School Diploma or GED	0.05
American Indian or Native	0.03	Some college or 2-year degree	0.15
Other Race/ethnicity	0.02	Bachelors degree	0.55
I am unsure or I prefer not to say	0.01	Some graduate work	0.03
Identify as Hispanic/Latino	0.19	Masters professional or doctoral degree	0.21
Previous year preschool attendance	0.58		

To have more equal SES groups for data analysis, we collapsed the responses for both SES variables into three more equally-sized groups: less than a bachelor's degree, a bachelor's degree, and more than a bachelor's degree, and less than $45,000, $45,000–$89,999, and more than $90,000.

TABLE 2 Proportions and averages for parents' pedagogical approaches use and belief.

Pedagogical Approach Name	Full pedagogical approach	Proportion who used	Average importance rank	Proportion who used most often	Proportion who believed most important	Proportion who believed least important
"Daily living" approach	I give my child math-related tasks or ask math-related questions during ongoing daily living experiences or routines (e.g., we talk about numbers as we use measuring cups or spoons while preparing food).	0.73	2.19	0.45[a]	0.19	0.38
"Direct teaching" approach	I set aside time to focus on directly and intentionally teaching my child math skills (e.g., we use a math workbook or math flashcards).	0.52	2.77	0.20[a]	0.38	0.21
"Give math toys" approach	I enrich my child's playtime by providing math-related toys and materials that my child uses alone or with other children (e.g., my child spontaneously plays with playing cards or puzzles alone).	0.67	2.46	0.19	0.21	0.23
"During child enjoyment" approach	I incorporate math during activities that I think my child will enjoy or play math games with my child to engage my child's math interest (e.g., we talk about math while playing board games or watching Sesame Street together).	0.55	2.58	0.16[a]	0.22	0.18

[a]Significant difference to the proportion who believed this approach was most important.
When participants were asked to rank the approaches, they ranked them from least important = 1 to most important = 4.
$^{***}p<0.001$; $^{**}p<0.01$; $^{*}p<0.05$.

Table 3 shows the pedagogical approach used most often by parents' highest educational attainment and household income. Chi-square difference tests showed no significant differences for pedagogical approach used most often by educational attainment, X^2 (6, 329) = 11.66, $p = 0.07$, or household income, X^2 (6, 329) = 9.72, $p = 0.14$. However, a chi-square difference test for pedagogical approach use by whether their child attended preschool the year before the study suggested there was a difference, X^2 (1,332) = 13.73, $p < 0.01$. *Post hoc* comparisons with Bonferroni correction indicated that parents with a child who did *not* attend preschool the previous year more frequently selected the "during child enjoyment" approach as the approach they used most often compared to parents with a child who attended preschool the previous year, X^2 (1,332) = 10.24, $p < 0.001$.

Pedagogical approach beliefs

As shown in Table 2, and contrary to our hypothesis, parents most frequently selected "direct teaching" as the approach they believed was most important. The other three approaches were selected as most important by a similar proportion of parents. Parents most frequently selected "daily living" as least important. There was no significant difference in pedagogical approach believed to be most important by child age, as a categorical variable, X^2 (3, 341) = 5.06, $p = 0.17$, or continuous variable in months [X^2 (102, 242) = 119.351, $p = 0.11$], or by household income level, X^2 (6, 338) = 6.14, $p = 0.41$. A chi-square difference test for pedagogical approach believed to be most important by highest educational attainment suggested there was a difference, X^2 (6, 338) = 13.31, $p = 0.04$. *Post hoc* comparisons with Bonferroni correction indicated that parents with a bachelor's degree most frequently selected the "during child enjoyment" approach as most important compared to parents with less than or more than a bachelor's degree. Additionally, a chi-square difference test for pedagogical approach believed to be most important by whether their child attended preschool last year suggested there was a difference, X^2 (3, 341) = 15.24, $p < 0.01$. *Post hoc* comparisons with Bonferroni correction indicated that parents with a child who attended preschool last year more frequently selected the "during child enjoyment" approach as most important compared to parents with a child who did not attend preschool last year, X^2 (1,332) = 10.24, $p < 0.001$. Additionally, parents with a child who did not attend preschool last year more frequently selected "direct teaching" approach as most important compared to parents whose child did attend preschool last year, X^2 (1,332) = 11.56, $p < 0.001$.

Match in pedagogical approach use and beliefs

Most parents (83%) showed a mismatch in the approach they used most often and believed to be most important (see Table 4 for a contingency table of these variables). This mismatch was confirmed with a Chi-Square test of independence, X^2 (9, 335) = 33.16, $p < 0.001$. *Post hoc* comparisons with Bonferroni correction showed significant differences for the "daily living," "direct teaching," and "during child

TABLE 3 Proportion of parents who selected pedagogical approach most often and most important by education, income level, and previous preschool attendance.

		Most often[a]					Most important				
	N	Pedagogical approach proportion				X^2	Pedagogical approach proportion				X^2
		Daily living	Direct teaching	Give math toys	During child enjoyment		Daily living	Direct teaching	Give math toys	During child enjoyment	
Highest education	–	–	–	–	–	11.66	–	–	–	–	13.31*
< bachelor's degree	73	0.40	0.13	0.21	0.26		0.21	0.40	0.25	0.15	
bachelor's degree	189	0.44	0.24	0.19	0.13		0.15	0.38	0.17	0.29[a]	
> bachelor's degree	82	0.52	0.17	0.20	0.11		0.24	0.38	0.24	0.13	
Household income	–	–	–	–	–	9.72	–	–	–	–	6.14
< $45,000	95	0.44	0.24	0.16	0.16		0.22	0.35	0.22	0.21	
$45,000–$89,999	140	0.51	0.13	0.19	0.17		0.14	0.45	0.18	0.23	
> $90,000	109	0.38	0.26	0.23	0.13		0.21	0.33	0.23	0.23	
Previous year preschool attendance	–	–	–	–	–	13.73**	–	–	–	–	15.24**
Yes	198	0.44	0.24	0.21	0.10b		0.18	0.31b	0.23	0.28[b]	
No	146	0.46	0.14	0.17	0.23		0.19	0.49	0.18	0.14	

[a]Both parents with less than a bachelor's degree and with more than a bachelor's degree were significantly different from parents with a bachelor's degree, $p < 0.05$.
[b]Parents with a child who attended preschool the previous year were significantly different from parents whose child did not attend school, using Bonferonni correction ($p = 0.05/4 = 0.0125$).
***$p < 0.001$; **$p < 0.01$; *$p < 0.05$.

enjoyment" approaches, but no significant difference for the "give math toys" approach (see Table 2, columns 5 and 6).

Discussion

To the best of our knowledge, this was the first study to separately examine parents' use and beliefs about how to best support their children's math development at home. Additionally, the current study has an important strength compared to previous research on the HME by surveying both mothers and fathers. The previous three studies on pedagogical approach beliefs were almost exclusively with mothers.

The disconnect between pedagogical approach use and beliefs

Contrary to our hypothesis and findings in DeFlorio and Beliakoff (2015), parents in the current study, who were predominantly from middle- and high-SES backgrounds, most often selected a "direct teaching" approach as most important to their children's home math learning compared to three other informal approaches. This was more similar to prior findings with low-SES parents (Cannon and Ginsburg, 2008; DeFlorio and Beliakoff, 2015). We also did not find differences by parents' education level or income in the frequency of believing "direct teaching" to be most important, contrary to DeFlorio and Beliakoff (2015). At the same time, the combined frequency of selecting any of the three informal pedagogical approaches as most important indicated that parents were more likely to believe an informal approach was more important than a formal, direct teaching approach.

Turning to pedagogical approach use, parents in the current study tended to select the "daily living" approach as the approach they used most often. This finding provides support that pedagogical use is separate from belief. Indeed, parents' pedagogical approach beliefs did not align with what pedagogical approach they used most often. This mismatch held for individual parents - over 80% of parents did not believe the approach they used most often was most important to their child's math development at home. This disconnect may have important implications for how to support successful math learning at home. If parents believe a particular approach is most important for their child's success but are not engaging their child with that approach as often as with other approaches, updating their beliefs about the importance or usefulness of an approach may not change behavior. Another potential reason for this disconnect could be that because parents engage in less direct instruction with their children (20% used it most often), they might believe they should use the approach more and thus rank it as most important.

TABLE 4 Contingency table of pedagogical approach believe most important and use most often.

		Use most often				
	Pedagogical approach	Daily living	Direct teaching	Give math-related toys	During child enjoyment	N
Believe most important	Daily living	18	20	10	14	62
	Direct teaching	65	12	31	21	129
	Give math-related toys	29	20	8	14	71
	During child enjoyment	38	16	16	3	73
	N	150	68	65	52	335

N is 335 instead of full sample (*N* = 344) due to 9 participants missing use and use most often question.

Parents' pedagogical approaches align somewhat with the broader literature on pedagogy in teaching. The "daily living" and "during child enjoyment" approaches share similarities with guided play and guided participation, the "direct teaching" approach shares similarities with direct instruction, and the "give math related-toys" approach shares similarities with play-based and child-initiated play. In this way, pedagogical approaches can be compared and discussed with findings in the teaching literature. In fact, similar to the current study, there is a disconnect between teachers believing children can learn from play but still mostly using direct instruction (Kim, 2004; Pui-Wah and Stimpson, 2004; Pyle et al., 2017). These parallel pedagogical disconnects suggest implications for our findings, for, not parents alone but, perhaps all adults who interact with learners. Importantly, while both teachers and parents have a disconnect in their pedagogical behaviors and practices, they used and believed opposite approaches were most important. Teachers tend to use mostly direct instruction and believe play is important while parents tend to use play and believe direct instruction is most important. Future research should examine explanations for common threads between these disconnects and what might explain these differences (e.g., messages schools and society send about direct instruction and preparation for formal schooling which potentially emphasizes direct teaching to parents but play to teachers, social desirability, and the impact of experience and routine for teachers compared to parents). For example, previous research highlights the impact of additional variables like parent-educator communication on parents' math support (Lin et al., 2019).

One related variable to parent-teacher communication that we collected in the current study was if the child had attended preschool last year. The current study found a relationship between children's past preschool attendance and pedagogical approach use and belief. Similar to the typical findings with teachers about playful learning versus direct teaching (Kim, 2004; Pui-Wah and Stimpson, 2004; Pyle et al., 2017), parents with a child who attended preschool last year less frequently reported the "during child enjoyment" approach as the one they used most often and less frequently reported the "direct teaching" approach as the one they believed was most important compared to parents with a child who did not attend preschool. These results and their movement away from the trends we saw with overall parents suggest parents may be getting and internalizing that messaging from teachers and their child's school. However, parents with a child who attended preschool also more frequently reported the "during child enjoyment" approach to be the one they believed most important over parents whose children did not attend preschool the previous year. This result suggests parents with a child who attended preschool the previous year, like our overall results, believe an informal approach is most important. Importantly, the current study only asked about preschool last year, so we do not have data on whether the child was currently attending preschool when the parent filled out the survey.

Additionally, we did not find a relationship between child age and pedagogical approach use or belief. Although previous literature has examined child age as a factor influencing the HME, DeFlorio and Beliakoff (2015) is the only other study so far to examine pedagogical beliefs by child age. They found parents of four-year-olds were more likely to believe "give math-related toys" was most important" than parents of three-year-olds, but beliefs about the "daily living" and "direct teaching" approaches did not differ by child age. Combined with the current study, most pedagogical beliefs do not seem to differ for parents of 3- vs. 4-year-old children. However, age-related differences in pedagogical approach beliefs and use are much more likely in a wider age range.

Overall, the current study found little evidence for SES differences in pedagogical approach use or belief by parent income or education level. We found parents who believed the "during child enjoyment" was most important were significantly different by educational attainment compared to other parents, but there were no significant differences by education or income for any other belief approaches or pedagogical approach use. Notably, our sample was largely well-educated and middle to high-income which limited our ability to detect differences.

Implications

Our results have implications for parental perceptions about the quality of their math support at home. Parents who know their actions to be inconsistent with their beliefs about what is most beneficial may develop self-doubt about the quality of support they are providing to their preschool children. Their beliefs and use of early math support may be shaped by messaging that they receive from media, parent-teacher communication, and other sources around approaches and activities that help their child learn math at home. Current research often relies on the frequency of specific activities to measure the HME. Further research is needed to explore how pedagogical approaches relate to the HME. Specifically, more work is needed on how the four pedagogical approaches align with different types of numeracy activities.

Furthermore, parents' belief that direct instruction was most important to their children's learning at home does not align with beliefs among psychologists that play-based learning is best for preschool-age children (Hirsh-Pasek et al., 2009; Weisberg et al., 2013; Skene et al., 2022). Perhaps parents' beliefs are shaped by educational or other resources about formal school readiness where direct instruction is emphasized. At the same time, most parents are using the informal, play-based approaches that psychologists suggest are best for preschool-age children. However, parents' other beliefs (e.g., beliefs about the importance of their child achieving specific math benchmarks, beliefs about their child's current math abilities) are uniquely predictive of the frequency and complexity of the math support parents provide their children at home (Douglas, 2022). Interventions geared at changing parents' beliefs about a pedagogical approach may not be enough; parents may not adopt approaches even if they are convinced that the approach is the most beneficial.

Limitations

One limitation is the current study only provides correlational evidence. Another limitation is that our sample was largely well-educated and middle-income, and few parents were on the ends of the economic spectrum, reducing the study's ability to detect SES-related differences. Additionally, MTurk has benefits as a convenient platform to collect a wider sample and research suggests MTurk is representative of the US population by gender and race (Burnham et al., 2018) and Cloud Research represents the US population well in income and education level (Moss and Litman, 2020). However, parents of young children on MTurk may differ from other MTurk participants. We must be careful since our sample was skewed toward highly educated and high-income participants, but this is also a common issue when recruiting from participant databases maintained by university psychology departments.

It is beyond the scope of this project to determine which approaches are optimal, but, if some approaches are actually more beneficial than others, our work has important implications for how to encourage parental use of an optimal approach. More research is needed to understand what frictions prevent parents from acting on their beliefs about what is most beneficial and parents' understanding of and feelings toward this misalignment.

Conclusion

HME research focuses on parents' beliefs and support, but little research has focused on the approaches parents take to support their children's math learning at home. We identified a disconnect between parents' pedagogical approach use and beliefs suggesting that the ideas that parents have about what they should do differ from what they are doing. Overall, there is still much to learn about parents' beliefs about the HME and how researchers can best influence the adoption of beneficial approaches to support children's math development at home.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Vanderbilt University Institutional Review Board. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

CM: project design – conceptualizing the current study questions and revising pedagogical approach measure, data collection, writing – initial draft, and further edits. A-AD: project design, data collection, writing – reviewing and editing, and project administration. BR-J: supervision, writing – reviewing and editing, and project administration. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2023.1114803/full#supplementary-material

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Virtual Teaching Together: engaging parents and young children in STEM activities

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Introduction: Early informal learning experiences are essential for sparking long-term interest in science, technology, engineering, and math (STEM). In a prior study, we found more promising parent involvement outcomes when families of young children were provided with STEM family education events along with home STEM activity kits compared to providing workshops alone. This study was a conceptual replication using the same program—*Teaching Together STEM*—to deliver educational workshops plus home activity kits; however, we varied the delivery method by using virtual "funshops" to evaluate if parents perceived this modality as feasible and useful.

Methods: Museum informal science educators introduced four units via virtual video chat sessions linked to 12 hands-on STEM activities that were mailed to families randomly assigned to the treatment group. Half of the families were assigned to a waitlist control group that received a portion of the virtual program after the posttest. Participants included 60 families with children aged 3 to 5 years from diverse linguistic and socioeconomic backgrounds.

Results: Our results indicate no significant group differences in the primary outcome of parents' involvement in informal STEM but a small, positive effect size (ES = 0.18) that was similar in magnitude to the prior, in-person study. Although parents mostly perceived the remote delivery as convenient and the materials as engaging for their child, there were no significant program impacts on children's general science interests (ES = −0.19).

Discussion: Despite the convenience, parents reported time was a barrier to doing STEM activities at home. Parents with lower education levels were less likely to attend, suggesting virtual approaches are not sufficient for ensuring broad access to family engagement programs for populations underrepresented in STEM.

KEYWORDS

outreach, learning, STEM, family engagement, preschool

Introduction

This study examined the promise of reimaging a science, technology, engineering, and math (STEM) family engagement program with virtual facilitation. We designed a conceptual replication study that shifted from past in-person events to remote delivery of family education workshops called *Teaching Together STEM* (*TT STEM*). In this study and the past in-person version, the program was delivered by the same team of museum-based, informal STEM educators (hereinafter, "STEM educators"). We evaluated the promise of these virtual family "STEM funshops" using feasibility and usability outcomes and by comparing parent and child outcomes for the treatment group to a waitlist control group. This study occurred within 1 year into the global COVID-19 pandemic, and we designed the program for potential use beyond emergency contexts. If promising, virtual support for doing STEM at home might be part of our "new normal" post-COVID by providing unique spaces for families from diverse cultural and linguistic backgrounds to explore science and math with young children (Pattison et al., 2020; Zulirfan et al., 2020). Indeed, libraries and other community organizations increasingly offer virtual community engagement services that merit further evaluation (Evener and Chase, 2022).

Broadening access to early STEM family engagement

Virtual family engagement approaches warrant study for two reasons. First, parents and caregivers report barriers to attending in-person family engagement events due to limited time or work and conflicting family schedules (Heath et al., 2018; Zucker et al., 2021, 2022). Nationally, only 6% of students have a parent attend school-based parent education workshops (National Center for Education Statistics, U.S. Department of Education, 2021). Virtual offerings could increase family attendance at educational events because it is a more convenient, flexible learning environment (Raes et al., 2020; Takeuchi et al., 2021) that could allow busy families with competing time priorities to do playful science activities when it best fits their schedule. However, there are potential challenges to virtual learning, such as reduced quality of interactions with the educator and other learners as well as potential for technology glitches or access issues (e.g., weak internet access speed; limited competencies for online platforms; Sullivan and Strawhacker, 2021).

Second, U.S. parents have less awareness of how to support their young child's science and math skills compared to literacy (e.g., Sonnenschein et al., 2021). Yet, the U.S. needs to increase students' general interest in STEM fields (National Research Council, 2009, 2012; Coley et al., 2020) to create pathways to long-term STEM interests and careers (Pattison et al., 2022). An important feature of early informal STEM experiences is to broaden access to address science and math learning opportunity gaps that begin early for students experiencing socioeconomic disadvantage as well as students who are Hispanic, Black, or American Indian (e.g., Morgan et al., 2016). Parents who speak languages other than English or parents with less formal education may particularly benefit from family engagement experiences that explain developmentally appropriate ways to get involved in their child's learning and allow them to select their preferred language for STEM learning (Garibay, 2007; Green et al., 2007). Museum-based educators, librarians, and educators can host educational events to support parents of young children with messages, such as "science is for home, school and all the places in between…science is watchable, readable, playable and doable" (p. 52, Silander et al., 2018). Realizing how STEM is part of young children's daily lives can empower parents to explore these concepts (e.g., Garibay, 2007; Šimunović and Babarović, 2020) and debunk common misunderstandings about who can do "real science" (e.g., Leblebicioglu et al., 2011).

Rationale for our approach

Early science interest is important for developing a perception of yourself as someone who is capable of doing STEM (Kim et al., 2018; Lent et al., 2018; Archer et al., 2020). A major aim of our program was to increase children's *interest in science*, which we conceptualized as a positive attitude, enjoyment, or value of doing science-related activities (Bell et al., 2019). Opportunities for increasing young children's science interests are often playful and build off children's questions about the world (e.g., Wolfgang et al., 2003; Casey et al., 2008; MacDonald et al., 2020).

Parents and caregivers play an important role in supporting children's early science interests and STEM knowledge. The primary aim of our program was to increase *parent involvement in STEM* that includes home-based learning such as counting, comparing, talking about the natural world, and exploring STEM concepts that involve causal reasoning, problem-solving, or technical vocabulary (e.g., Haden et al., 2014; Silander et al., 2018; Cian et al., 2021). This was our primary outcome because parents of young children are the purveyors of many early STEM experiences and play key roles in shaping their children's attitudes about STEM (e.g., Jacobs and Eccles, 2000). Parent involvement in learning activities is broadly related to student academic achievement (e.g., Sheldon and Epstein, 2005; Barnett et al., 2020; Ogg and Anthony, 2020). We aimed to increase parent involvement in STEM via a series of four virtual "funshops" and by mailing families hands-on STEM activities linked to the unit of study (Caniglia et al., 2021). We also sent parents follow-up text messages with tips and extension activities (Santana et al., 2019) and family museum passes (Vandermaas-Peeler et al., 2016; Pagano et al., 2020).

Evidence for virtual learning

There are few rigorous experimental or mixed-method studies on the effectiveness of online learning for students in preschool to Grade 12 (Means et al., 2013; Poirier et al., 2019). To date, virtual or hybrid STEM research with young learners has mostly occurred in formal learning settings by integrating multimedia into classroom-based instruction (e.g., Rosenfeld et al., 2019). A few studies demonstrate the potential benefits of the virtual learning approach for preschool children and their parents in informal learning settings (e.g., McCarthy et al., 2013). Young children can gain knowledge from pre-recorded educational media that encourages extensions via social learning with caregivers (e.g., McCarthy et al., 2013; Rosenfeld et al., 2019; Neuman et al., 2020). Preschoolers can be as responsive to conversations through video chat platforms like Zoom as they are to in-person conversations; they also have similar vocabulary and comprehension benefits via video chat compared to in-person modalities (Gaudreau et al., 2020). For parents, there is some evidence that their attitudes and abilities to support their child's learning improve after participating in virtual learning programs (e.g., Pasnik et al., 2015). Thus, there is initial evidence that virtual approaches to engaging children and families in STEM warrant further research using rigorous experiments and implementation science lenses that consider outcomes, such as feasibility and usability (e.g., Proctor et al., 2011; Atkins et al., 2017).

Current study

The *TT STEM* program is designed for 3- to 5-year-old children to explore science, math, and engineering concepts with support from a parent or caregiver (hereinafter, referred to as parents, given that was the majority of our sample). We modified the existing, in-person *TT STEM* "funshops" due to COVID-19, but we hoped this virtual approach might prove useful post-pandemic. This was a conceptual replication study because we hypothesized that the virtual version of the TT STEM program could produce small increases in parent involvement in science and math commensurate in magnitude with effect sizes [ES] observed in an earlier, in-person study (ES range = −0.08 to 0.18; Zucker et al., 2022). Both the prior study and the current study used very similar materials and methods, such as the same STEM educators as funshop facilitators and a series of follow-up text message reminders and extension activities after each event. We primarily compared the virtual treatment group of this study to a waitlist control group of families; moreover, we also compared the magnitude of effect sizes in this virtual study to the prior in-person version of the program. Our recruitment approach included both schools that were partners in the first study and social media; this resulted in a sample of families from diverse socioeconomic, racial, and linguistic backgrounds. We expected linguistic diversity and, thus, offered a bilingual program with a choice of English or Spanish virtual sessions and text messages. We used an experimental design and mixed method data sources to understand if this virtual approach improved key parent and child outcomes and was feasible for families to take part in. We addressed the following three research questions (RQ):

1. To what extent was the virtual treatment feasible and useable in terms of parent perceptions, session attendance, activity utilization, and overcoming parents' perceived barriers to doing STEM at home?
2. Did the program impact parent involvement in informal STEM learning?
3. Did the program impact children's science interests?

For the first set of implementation outcomes, we expected variability in parent attendance but that the virtual program would reduce barriers to doing STEM at home. In regard to measures, we hypothesized the parent involvement survey that assessed several ways of doing science and math within the family's daily routines to be appropriate to detect effects. We also gathered qualitative data describing how parents supported their child's learning in ways that fit their unique family context. We were not certain if the rather generalized child interest survey would be sensitive enough to detect changes; however, it aligned with our logic model and other similar approaches that theorize early family participation in informal STEM can promote long-term STEM interest (e.g., Pattison et al., 2022).

Methods and materials

This study was conducted in 2021—as the COVID-19 pandemic was ongoing—by university-based researchers and museum-based STEM educators in a research–practice partnership. Participants included 3- to 5-year-old children and their parents. We recruited via school-based flyers and online/social media advertising (i.e., Museum and University's social media and newsletters). Most families resided in an urban U.S. city where the Children's Museum Houston is located; however, a few were recruited via social media from rural areas in this U.S. state. We recruited 60 families and randomly assigned 30 to waitlist control and 30 to treatment. As detailed in Table 1, approximately, 48% of the children in the sample were girls (M_{age} = 4.67 years, SD = 0.57), and 50% of families spoke a language other than English. Among these families, nine selected Spanish as their preferred language of communication. For ethnicity, 42% reported that their child was Hispanic. In terms of child's race, the sample was 63% white, 28% African American, 13% Asian, and 5% other. Mothers' median education was a master's or postgraduate degree, and fathers' median education was a bachelor's degree. Median household income was $40,001–$70,000 (missing data for n = 12) with a sizeable range from ≤$11,000 to ≥$150,000. Approximately 38 and 55% of mothers and fathers reported a STEM-related career, respectively. Children participated in two formal education settings: 30 different early childhood centers (90% of the sample) and homeschooling (10%). Parents/primary caregivers provided written informed consent (Study #HSC-MS-15-0759) prior to their inclusion in the study. We randomized families without accounting for baseline demographics; however, language preference was relatively balanced across conditions, with five Spanish-speaking families assigned to the treatment group and four Spanish-speaking families in the control group.

Treatment procedures

The virtual *TT STEM* funshops were delivered across 10 weeks (March–May 2021) and addressed four units detailed in Supplementary Table S1. Two bilingual (English/Spanish) Hispanic female STEM educators with 11 and 19 years of experience in family engagement delivered sessions. Five treatment families (16.7%) selected the Spanish version of the sessions and text messages. Table 2 shows screenshots of key steps from unit 1. Each unit included the following five procedures:

1. **Mailed activity kit**: the museum educators mailed families a kit of three activities about one week before each unit introduction chat was scheduled (12 total activities).
2. **Introductory chat**: in a 20-min synchronous video chat, STEM educators used an icebreaker activity to generate excitement for the "funshop" thematic unit. Next, the facilitator introduced the unit topic and kit activities. Families used their own devices to join a Zoom meeting in their preferred language (English-4:30 pm or 5:30 pm; Spanish-4:30 pm).
3. **Home activities**: families were sent English or Spanish text messages with a link to YouTube channels created by the museum and designed for parent–child co-viewing to include the following: (a) unit introduction, (b) STEM educators read-aloud modeling focal parent strategies, and (c) three videos with instructions/models for each of three kit activities. Each activity included bilingual step-by-step instructions with photos to minimize reading demands.
4. **Follow-up chat**: approximately 2 weeks later, in a 20-min Zoom follow-up discussion, families were encouraged to share artifacts from their completed projects and discuss what they remembered or learned with activities.
5. **Extensions**: parents received text messages with tips to continue supporting their child's STEM learning to use the

TABLE 1 Participant baseline demographic characteristics and balance check for posttest analytic sample (n = 50); means and (standard deviations).

	Treatment (n = 23)	Control (n = 27)	Unstandardized regression coefficient (attriters—non-attriters)	Difference as effect size	p-value
Demographic and family characteristics					
Child female?	0.43 (0.51)	0.48 (0.51)	−0.05	−0.09	0.747
Other language at home?	0.48 (0.51)	0.56 (0.51)	−0.08	−0.15	0.595
Mother's education[a]	6.78 (2.43)	6.70 (2.71)	0.08	0.03	0.915
Father's education[a]	5.87 (2.90)	5.30 (3.07)	0.57	0.19	0.503
Mother STEM-related career	0.30 (0.47)	0.37 (0.49)	−0.07	−0.13	0.632
Father STEM-related career	0.57 (0.51)	0.53 (0.49)	−0.06	−0.13	0.651
Is child hispanic?	0.45 (0.51)	0.41 (0.50)	0.05	0.09	0.746
Child's race					
Black/African American	0.30 (0.47)	0.19 (0.40)	0.12	0.30	0.335
White	0.70 (0.47)	0.63 (0.49)	0.07	0.13	0.632
Asian	0.09 (0.28)	0.22 (0.42)	−0.14	−0.32	0.201
Other	0.00 (0.00)	0.07 (0.27)	−0.07	−0.28	0.190
Household income[b]	4.71 (2.05)	5.59 (2.03)	−0.89	−0.43	0.189
Baseline outcome measures					
Parent involvement[c]	2.65 (0.53)	2.49 (0.50)	0.16	0.32	0.283
Child STEM Interest[d]	3.53 (0.43)	3.44 (0.45)	0.09	0.20	0.481

[a]Education was measured as an 8-category variable ranging from 1 to 8, where 1 represents <=8th grade and 10 = master or postgraduate degree.
[b]Household income was measured as an 8-category variable ranging from 1 (11 K or less) to 8 ($150 K or more).
[c]Ranges from 1 = none to 4 everyday.
[d]Ranges from 1 = strongly disagree to 4 = strongly agree.
Overall F-test for the posttest sample, where all variables listed in the table were used to predict attrition, was statistically significant, F (18, 20) = 1.37, p = 0.247.

strategies modeled by the STEM educators in extension activities linked to the theme but using common household objects (see Table 2).

At the conclusion, participants received a family pass ($72 value) for museum entry, when it reopened in June 2021 after COVID-related gallery closures. The logic model for this treatment approach is illustrated in Supplementary Figure S1. The materials mailed to families were exactly the same as the in-person funshop materials mentioned in our study, but we selected a portion of past materials because we only delivered four of the six available workshop themes in this brief virtual intervention. We also did not send the nine supplemental materials given in two groups of our prior study (B and C; Zucker et al., 2022) because that would have resulted in a likely overwhelming number of activities for parents to use and because the cost of mailing these exceeded typical museum outreach budgets. The text messages and facilitators in modeling videos were exactly the same as in our initial study.

Waitlist control procedures

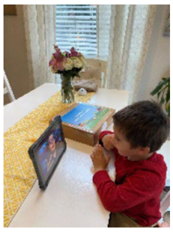
The waitlist control group received one unit on a delayed schedule *after* the posttest (i.e., the posttest was completed by June, and the virtual waitlist program was offered in July 2021). STEM educators delivered the first unit only (What's the Big Idea) using procedures #1–4 mentioned above. That is, families were mailed one kit and took part in the video chats with a STEM educator. Limited resources prevented us from offering the full series of virtual themes. Waitlist control families did not receive text messages, as this followed an automated schedule that matched the larger intervention delivery schedule.

Measures

Given that this was a pilot, we used a brief online parent survey to capture only a small number of key outcomes. The pretest occurred from mid-January to February 2021, and the posttest was in June 2021. Upon completion, families received a $25 eGift card. Table 3 reports descriptive statistics and missing data details. The primary outcome was a quantitative measure of parents' home-based involvement. *Parent involvement in STEM* was measured with nine items about the frequency of STEM-related activities. Items were adapted from the Head Start Family and Child Experiences Survey (FACES; West et al., 2007), such as: "How many times in the past week have you compared sizes of objects or toys with your child?" "How many times in the past week have you talked to your child about plants, animals, or other living things?" These were the same items used in our past study (Zucker et al., 2022).

We also gathered qualitative data related to how parents supported their child's STEM learning. During the program, we asked treatment and control parents to send us a short text message in response to this prompt: "Tell us about an activity you did with [child name customized here] this week to support his/her learning." We requested three texts from treatment parents and received 24 written replies (26.7% response rate)

TABLE 2 Virtual teaching together STEM cycle of activities.

Modality	Activity description	Screenshot/Photos
N/A	**Preparation**—mail kits with links to Zoom meeting times/details. Send text reminders. Login to Zoom meeting.	
Synchronous	**Intro video chat**—welcome and preview activities and parent strategies (15–20 min). Every 2 weeks, a new unit was introduced with hands-on icebreaker activity ISE guided families to complete together.	
Asynchronous	**Unit kickoff video**—explains how to do science and math with young children. Explains parent strategies of using big words and asking open-ended questions	
	Read aloud video—informal STEM expert from museum model strategies during read-aloud of a text	
	Activity preview videos—Informal STEM expert from the museum explains each of the three activities in the family's mailed kit	
Asynchronous[a]	**Parent–child home activities**—Family completes the STEM activities in their mailed kit using detailed instructions from ISE with linked bilingual YouTube video demonstrations	
Synchronous	**Follow-up video chat**—Show and tell about STEM activity/creations and request to complete a feedback survey (20–25 min)	
Asynchronous	**Extensions**—Parents receive text messages with tips and extension activities to further increase parent involvement in STEM activities	

[a]Parents were sent a QR code and a link with video instructions that were in their preferred language. Theme 1 instructional videos are available at this YouTube channel in English https://www.youtube.com/playlist?list=PLPZCH1CZOF9IJPQOxPJ0Xp0fkp8egc_NG and here in Spanish https://www.youtube.com/playlist?list=PLPZCH1CZOF9JhZI7gtiCwYEvgXAJBakzZ.

TABLE 3 Descriptive statistics for outcomes for analytic sample ($n = 50$); means and (standard deviations).

	Treatment (n = 23)		Control (n = 27)	
	Pretest *M* (SD)	Posttest *M* (SD)	Pretest *M* (SD)	Posttest *M* (SD)
Parent involvement[a]	2.65 (0.53)	2.73 (0.45)	2.49 (0.50)	2.57 (0.69)
Child STEM interest[b]	3.53 (0.43)	3.64 (0.47)	3.44 (0.45)	3.60 (0.43)

[a]Range from 1 = none to 4 everyday.
[b]Range from 1 = strongly disagree to 4 = strongly agree.

and two times from control with 18 replies (30.0% response rate). With the treatment group only, we also used an exit survey after each theme. The exit survey asked about which read-alouds and provided STEM activity kits they used as well as their parent involvement goals ("How do you plan to support your child's learning?"). This exit survey was accessible at the end of the video chat with QR codes and was also sent to all treatment parents with links to text messages scheduled after the follow-up sessions. We had 41 qualitative responses across all four exit surveys, resulting in a relatively low response rate of 46.0%. At posttest only, we had a secondary, qualitative measure tapping STEM barriers ("What do you think are the top barriers to families doing science and math activities at home?").

The primary child outcome was a general interest in science, as rated by their parent. We adapted items from the *Student Interest in Technology and Science* (SITS; Romine et al., 2014). This included three items about learning ("My child enjoys learning science"; "My child likes it when we find ways to do science outside of school") and one career item ("I think my child would like to work in a science-related career one day") on a 4-point scale from *1* = strongly disagree to *4* = strongly agree. Internal validity for this sample was $\alpha = 0.80$. A secondary measure for treatment families was children's interest in the virtual *TT STEM* program activities. We asked families about each unit's three activities (12 total) and how interested their child was in these individual activities with a 5-point scale (*1* = extremely interested, *5* = not at all interested). These child interest measures were not used in our initial study but were added in this replication to assess more aspects of our logic model.

Data analysis

The analysis plan was pre-registered using the Registry of Efficacy and Effectiveness Studies (Registry ID: 9800.1v1); however, we deviated from the original pre-registration plan that had expected primarily school-based recruitment; however, adding school-level fixed effects was not appropriate, so we dropped that model. We estimated the intent-to-treat (ITT) of being assigned to participate in treatment using OLS regression, using the equations below, where Y is the parent or child-level outcome, i denotes child or parent, and s denotes school. We included the pretest score β_{2s} and child-level covariates β_{3s}:

$$Y_{is} = \beta_{0s} + \beta_1 \left(\text{Treatment}_s\right) + \beta_{2s}\left(\text{Pretest}_{is}\right) + \varepsilon_{is} \qquad \text{[Model 1]}$$

$$Y_{is} = \beta_{0s} + \beta_1 \left(\text{Treatment}_s\right) + \beta_{2s}\left(\text{Pretest}_{is}\right) + \beta_{3s}\left(\text{Covariate}_{is}\right) + \varepsilon_{is} \qquad \text{[Model 2]}$$

Model 1 adjusts for pretest scores and basic controls; Model 2 adds adjustments for child demographics. To examine qualitative data, the lead and second author reviewed transcripts of verbatim responses and coded them using implementation science domains (Atkins et al., 2017). We calculated inter-rater agreement (92%) and reached a consensus on conclusions.

Results

We detail participation in study activities and attrition in Supplementary Tables S3 and S4. These tables show no significant baseline group differences but marginal trends. Attrition was higher in the treatment than in the control group. Treatment parents were more likely to attrite at posttest if they had lower education levels.

RQ1: treatment feasibility

Perceived satisfaction

Parents were assigned to treatment completed satisfaction surveys using a Likert scale (e.g., *1* = very useful, *5* = not useful; e.g., "How helpful were the YouTube funshop videos in helping you and your family learn new ways of doing science and math at home?"). Ratings of satisfaction immediately after funshops ($n = 41$ responses) suggest good approval, $M = 1.79$ (SD = 0.98). At posttest, over 90% of parents ($n = 20$ respondents) said that the *TT STEM* program was helpful: (a) initial, synchronous video sessions, $M = 1.32$ (SD = 0.58); (b) YouTube videos explaining activity kits, $M = 1.26$ (SD = 0.45); (c) follow-up, show-and-tell video sessions, $M = 1.32$ (SD = 0.48); (d) text messages with parent tips, $M = 1.35$ (SD = 0.59); and (e) text message extension activities, $M = 1.35$ (SD = 0.49). Parents' open-ended responses indicated key benefits were convenience and the ability to select English or Spanish sessions. Similarly, interviews with STEM educators indicated they would like to "maintain virtual and in-person formats so families can choose what works better for them…we are facing a new era where technology is the 'main character'. So, we need to offer virtual sessions – not just for an emergency." Both STEM educators reported greater self-efficacy for facilitating in-person family events than virtual family events. For example, one ISE explained "sometimes we missed the fun" during virtual events. She elaborated, "There's a difference between the excitement in person—when they walk in the room, they are already excited. They see all the activities…they are like 'wow!' They cannot wait to try them out. But in virtual, I feel like they still were able to get excited because they would get this beautiful box in the mail that had these awesome activities that they could not wait to get their hands on. So, I think that it still had some level of excitement".

Attendance

Research staff joined video sessions to log attendance. The majority (73.33%) of treatment families attended at least one *TT STEM* Zoom session, with an average attendance of 39.58% for the eight Zoom sessions. Only two families attended all eight video sessions. The unit introductions had higher attendance ($M = 46.67\%$) than the follow-up sessions ($M = 32.50\%$). Supplementary Table S5 details attendance by workshop and language. Using separate OLS regressions, we examined if family characteristics predicted attendance: mother/father education, mother/father reported STEM job, household income, and race/ethnicity. We found that higher levels of maternal education were associated with higher attendance ($p = 0.034$). For race, we found that parents who self-identified as Black/African American had lower attendance ($p = 0.013$). For families that did not attend two or more funshop events, most reported reasons were competing priorities of work, childcare for other siblings, or limited time. Two parents reported their children's lack of interest in the video sessions as the reason for limited participation. No families reported internet or technology barriers.

Use of STEM activities

Treatments parents reported in an exit survey on their utilization of the provided activities. Treatment families reported that they utilized most of the provided YouTube read-aloud (85%) and at least two of the three provided activities (85%) in each of the four thematic events. However, we had a low response rate for these parent surveys, which could suggest that about half of families did not utilize the materials, which would bring average utilization down to a low rate of about 39%. More detailed activity usage data for each unit are in Supplementary Table S6.

Parent involvement barriers

At the posttest, we asked treatment parents to describe barriers to doing STEM with their children. The most salient barrier to parent involvement was *Limited Time* ($n = 11$ of 20 respondents, 55%). This theme was exemplified by responses such as "Time and energy. Our busy schedules require so much from parents, but this was a nice reminder that many everyday activities can be science and math activities too." Several parents who noted limited time was a barrier also said that the program helped them later STEM learning into their existing family routines. For example, one parent listed "Time to organize and plan" was a barrier, but said until this program she was "unaware of simple ideas and ways to be creative with objects around the house. I think these things come naturally to educators, but not everyone." The second part of her response was further coded for the barrier of limited *Information/Knowledge* ($n = 6$, 30%) that included similar parent barriers such as "not knowing what type of projects to do with a child. Receiving ideas was awesome and helpful." Additionally, five parents (25%) said lack of *Resources/Materials* was a barrier to doing science and math activities at home, saying their challenges were as follows: "Availability of material" or "Ideas, supplies." Despite these barriers, several parents learned that specialized STEM materials were not the only way to promote learning, saying, "Realizing that parents do not need to buy additional materials. Using what is available like [counting] the chairs in the house or cereal bits to count".

RQ2: parent involvement

Contrary to our expectations, there were no main effects on parent involvement in STEM from the quantitative Likert scale survey asking how often families did various types of STEM activities in a typical week—see Table 4. The effect size (ES) was small ($ES = 0.18$, $p = 0.618$). However, qualitative analysis of parent text messages and posttest surveys indicated that treatment parents reported various new ideas, goals, and ways they were supporting their child's STEM learning.

The most prominent strategy, reported by treatment parents in 44.9% of responses ($n = 22$), was *Observing/Reasoning* as they collected data or made comparisons with their child—a strategy emphasized in funshop 3 but present in all events/activities. For example, one parent explained how they promoted observing and reasoning during cooking: "Nosotros seguimos instrucciones de una receta para un pan de plátano. Buscamos los ingredientes. Los separamos en seco y mojado. Hablamos en cuanto el procedimiento y vimos el proceso de crecimiento del pan. Y al final lo disfrutamos (English translation: we followed instructions from a recipe for a banana bread. We looked for the ingredients. We separated the dry and wet. We talked about the procedure and saw the process of growing the bread. And in the end we enjoyed it)."

The next most common strategy treatment for parents, reported in 38.8% of responses ($n = 19$), was *Adapting/Extending* the provided STEM activity to promote additional informal learning—an approach emphasized in all funshops. This was exemplified by a response from a parent who adapted and extended the provided color mixing activity

TABLE 4 Main impact models comparing treatment group to control condition.

	Model 1				Model 2			
	ITT	Standard Error	*p*-value	ES	ITT	Standard Error	*p*-value	ES
Parent involvement								
Treatment	0.08	0.14	0.573	0.16	0.09	0.18	0.618	0.18
Child science interest								
Treatment	−0.02	0.10	0.816	−0.05	−0.09	0.11	0.456	−0.19

The control condition is the reference value (0), and treatment is set to 1. Treatment refers to the virtual workshops and TT STEM program. Basic controls refer to the language of the measure and the child's age in months. Child demographic characteristics refer to the child's gender, race, ethnicity, and highest education from a caregiver.
ES = effect size.
$+p < 0.10$; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

by using new materials to promote literacy: "We mixed finger paint colors in shaving cream to make new colors and practiced handwriting in it." This response was also coded for *Literacy,* which was a minor theme, with 14.3% ($n=7$) treatment parents reporting that they embedded literacy (writing and reading) in their STEM explorations.

The third most common way parents promoted STEM was *Numeracy* ($n=15$, 30.6%), which was the focus of the funshop 2. Numeracy was coded in parent statements such as, "We played Monopoly counting money and spaces." or "[We are] counting more objects around us".

Multiple parents reported goals related to *Asking Questions/ Promoting Curiosity* ($n=8$, 16.3%)—a theme introduced in funshop 1 and promoted throughout the program. Parents expressed goals, such as "encouraging the engineering spirit by providing materials and letting them create whatever comes to mind." Another parent mentioned promoting their child's interest in technical vocabulary, such as *experiment, estimate,* and *exploring.*

A small number of parents ($n=5$, 10.2%) reported involving their child in *Problem-Solving/Engineering Design* activities—the focus of funshop 4. A sophisticated example included: "We learned about thermodynamics and heat transfer when our fan to our condensing unit stopped operating. We were able to use water and air to remove the heat from the refrigerant as it passed through the compressor. I had him and his sister testing the resistance across a fuse in our HVAC unit".

Although only 10 of the 30 waitlist control parents provided qualitative responses about their involvement in their child's STEM learning, the most commonly reported strategy was promoting *Observing/Reasoning* about things in the natural world ($n=5$); this was also the strategy most frequently reported by the treatment parents. One control parent reported, "We have been going outside in the evenings finding ladybugs and explained how they lived and what they ate." The second most common theme reported by parents in the control group was *Literacy* ($n=4$). For example, one control parent said, "(Child name) loves reading so we usually snuggle up and read together. We also made a bookmark and wrote a letter for the teacher, as Teacher's Day is coming up".

RQ3: child outcomes

The primary child outcome was parents' report of their child's interest in STEM. No statistically significant effects were detected for parent reports of the child's general interest in STEM. The effect size was −0.19 ($p=0.456$); see Table 4. We asked treatment parents to rate their child's interest in the *TT STEM* activities kits mailed to each family. Parents consistently rated their child's interest level as "extremely interested" in the *TT STEM* kit activities ($M=1.43$, $SD=0.14$) on a 5-point scale (*1*=extremely interested, *5*=not at all interested).

Discussion

We evaluated the feasibility and promise of a brief virtual *TT STEM* program focused on four STEM units, which we revised for remote delivery by museum-based STEM educators. Despite positive feedback, there were no significant impacts of this virtual delivery of the *TT STEM* program on the primary survey measures of parent involvement and child STEM interest. However, there were positive qualitative themes demonstrating substantial involvement in informal STEM activities. The most important findings from this research relate to how virtual approaches may increase informal STEM learning convenience and accessibility in some meaningful ways. However, there were salient limitations to the virtual modality that limit the promise of entirely virtual modalities for future STEM family engagement programs.

Limited virtual impacts on primary parent outcome and shifted responsibilities

Our primary goal was to increase parents' frequency of engaging their children in home-based STEM learning, as parent involvement is positively linked to student achievement (e.g., Sheldon and Epstein, 2005; Barnett et al., 2020; Ogg and Anthony, 2020). Parents' qualitative responses indicated that the program showed them how to observe, estimate, explore, and count on their young children. There were small, non-significant increases ($ES=0.18$) in parents' reported frequency of STEM involvement. Although non-significant, effect sizes were similar in magnitude to past, in-person versions of this program (*ES* range − 0.08 to 0.18 at posttest; Zucker et al., 2022). On the one hand, these similar magnitudes of impacts on parent behaviors for in-person and virtual modalities may indicate that both approaches are suitable. However, we conclude that there are two major disadvantages to the virtual modality, discussed below, that suggest it is not currently suitable as a replacement for in-person family engagement events.

There are multiple potential explanations for these null parent findings. It is possible that there were no group differences because parents in both conditions were already rather involved in supporting their child's science learning at home; however, descriptively, families only reported doing STEM activities two or three times per week. Another explanation is that the virtual delivery was not of sufficient intensity to change parent behaviors. Indeed, potential challenges of virtual approaches are reduced intimacy with the facilitator and reduced social interactions with other families, which promote behavior change (Sullivan and Strawhacker, 2021). This reduced intimacy and interaction with the informal educator and other families in their community is the first shortcoming of the virtual approach. The STEM educators felt less efficacious when facilitating virtually because they could not answer questions and circulate the room to provide support while families did the STEM activities. Moreover, the qualitative responses from treatment parents indicated that limited time to do STEM with their children was the primary barrier to their involvement.

A second problem of the virtual modality is that the burden of facilitating informal STEM learning is largely shifted to parents in the virtual modality. Given that limited time was the primary barrier parents reported to doing informal STEM, it was likely challenging to ask these busy parents to find time to do 12 asynchronous STEM activities with their child. These exact same activities were not perceived as challenging or overwhelming to complete when families used them at prior in-person events and rotated through workstations where facilitators set up and demonstrated activities. For in-person facilitation, STEM educators also circulated the room, providing support and feedback as families completed activities. Indeed, there are more steps for parents to complete one of the four virtual units (i.e., (1) adding the Zoom session and links to the parent/family calendar, (2) logging into Zoom and attending introductory chat, (3) following texted links or QR codes to view instructional/modeling video for the first kit activity, (4) setting up materials for the mailed kit activity [some of which are messy], (5) completing the activity with your child [while reducing or ignoring competing priorities for parent's attention in their home], (6) repeating steps 3–5 for the next two activities in your kit, and (7) attending the debrief chat). These steps may be spread out over several days or periods of time that are convenient for the family. In contrast, with the in-person modality, parents are largely responsible for simply attending the funshop. There are not only fewer total steps for completing activities in person [i.e., (1) attending the event, (2) listening to instructions/modeling by museum educators, (3) rotating through three to five activity stations, and (4) sharing out or debriefing with other families at the event], but there are also fewer cognitive and memory demands placed on parents when in-person because the facilitator sets up the space and guides participants through activities in one 60–75-min period. Parents must also be more responsive to their child's desires and motivation to participate in STEM activities when they pick the time to do these at home, whereas in the social context of in-person learning, most young children are eager to rotate through the stations with their parent/caregiver. In sum, the virtual modality reduced intimacy and support with the facilitator and shifted many responsibilities to parents to orchestrate a multi-step process of informal learning in ways that may have run counter to our goal of broadening, feasible access to STEM.

Limited child impacts for a brief virtual approach

Our primary goal for children was to increase their broad interest in science and math, but there were no significant gains and a negative trend on this outcome (ES = −0.19). Although treatment parents reported high interest for their children during the provided STEM kit activities, this high enjoyment did not transfer to group differences in a more distal parent report of their child's general interest in science. Given the lack of significant parent outcomes, the lack of impacts for children is not surprising. The limited duration of this brief four-unit program may also explain these null findings, as low-intensity family approaches are unlikely to impact children's outcomes (Grindal et al., 2016). Other measurement approaches would be more sensitive, such as in-depth parent interviews on children and family's STEM interests (Pattison et al., 2022) or innovative apps that allow slightly older children to check in during their informal STEM activities to document interest, setting, and engagement (Morris et al., 2019).

Key lessons learned for virtual family engagement programs

Museum-based STEM educators and other family engagement specialists ask transformative questions about where informal science learning can occur and how to broaden access (e.g., Ishimaru and Bang, 2016; Ash, 2022). This study reimagined a museum outreach program in a virtual modality to consider if it is feasible to remotely deliver the *TT STEM* program to socioeconomically and linguistically diverse families of young children. The primary affordances of virtual learning were high satisfaction with the quality of activities and the convenience of the virtual format for families. Another benefit was broadened geographic access, including some non-local families and a few families traveling with their STEM kits while joining remote sessions. Yet, a major barrier was that the program did not adequately reach subgroups who may have benefited most. That is, parents with lower education levels and Black/African American families were significantly less likely to attend virtual events. Thus, offering virtual options may be convenient but not sufficient for increasing equitable access and the uptake of family education program goals. These findings align with the literature on virtual approaches where typical benefits are convenience, but known challenges are reduced closeness with the facilitator, limited social learning opportunities, and technology barriers (Sullivan and Strawhacker, 2021; Takeuchi et al., 2021).

Regarding attendance, parents attended an average of 39.58% of virtual sessions. This is commensurate with rates of 35–60% attendance in other in-person family education research studies that do not pay parents to attend (e.g., Heath et al., 2018; Kim et al., 2019). Although 85% of responding parents used the provided STEM activities, we had a low response rate for these parent surveys; thus, if we assume a non-response is linked to not utilizing the activities, then just over a third of families would have utilized materials. Thus, we feel cautious in terms of drawing conclusions about how useable this type of virtual STEM program is for families of young children. We tried to alleviate barriers to the uptake of the program. Families could select a synchronous video session at a preferred time and language and could complete the asynchronous hands-on STEM kit activities at a convenient time and place. We texted parents' tips and links to online extension activities that minimized resource demands using only typical household objects. Yet, in this sample, the majority of parents reported the primary barrier to supporting science at home was time constraints. This virtual program's flexible scheduling for doing STEM activities did not alleviate these families' time constraints. For any busy parent with competing demands on their time, and particularly for families experiencing poverty, researchers need to continue to explore innovative, in-person approaches to layering STEM into places families already spend time, such as grocery stores, laundromats, and local parks (Bustamante et al., 2019), as well as innovative virtual approaches (McCarthy et al., 2013; Rosenfeld et al., 2019).

Limitations and future considerations for virtual replications

The most salient limitations of this study were the narrow set of outcome measures, the modest intensity of only four thematic units facilitated over 10 weeks, and the relatively small sample. This duration may not have provided enough content coverage and time for parent behavior changes and increased child science interest. A second limitation we noted above is that our generalized measure of child

STEM interest was based solely on parent reports, not observations. A third limitation is the COVID context. The salient challenges families were facing in balancing parental responsibilities while supporting their child's learning during the pandemic (Garbe et al., 2020) may have attenuated or skewed our findings. Indeed, this is likely an atypical sample of education-oriented parents who were willing to sign up for a family engagement program during the pandemic; however, this should have been equally skewed across the randomly assigned groups. Another limitation was differential attrition (i.e., higher attrition for the treatment group than waitlist control). We do not have reason to believe that the treatment was overly burdensome for all families, given high satisfaction ratings from parents. However, it was troubling to find great attrition for treatment. We are also troubled by the shifting of various logistical responsibilities from informal STEM educators to parents who had to coordinate many more steps for the virtual than in-person approaches.

There are important sampling and procedural differences to note when comparing the results of this conceptual replication study to the prior study (Zucker et al., 2022). First, in terms of generalizability, the first study recruited entirely from schools that served a majority of students experiencing economic disadvantage. The replicated study recruited a new sample of families from some of these same schools but also added recruitment via social media because of low initial enrollment. This resulted in a current sample that was more socioeconomically diverse than our initial study. Second, although we drew materials and procedures from the same TT STEM program as the initial study, there are inherent differences in the approach that is appropriate for virtual facilitation compared to in-person programs. We detail these differences in supplemental materials (Supplementary Tables S7, S8) that also include a checklist for how we organized the virtual procedures, which may be of interest to others considering hybrid family engagement models.

Conclusion

In sum, high-quality, virtual STEM family engagement approaches may be feasible, yet our initial findings do *not* suggest that offering virtual events alone can effectively disrupt inequitable access to STEM family engagement in ways that make meaningful impacts on parent involvement and child science interest. Thus, we conclude that future iterations of *TT STEM* should avoid entirely virtual modalities. We may include both virtual and in-person formats in future programs so families can choose what works for them. We encourage other educators to consider experimentation with hybrid options across a broader student age span while considering issues of digital equity and appropriate cultural and linguistic approaches for diverse families to help ignite their child's interest in STEM.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors upon request.

Ethics statement

The studies involving humans were approved by Committee for the Protection of Human Subjects at the University of Texas Health Science Center at Houston's McGovern Medical School. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin. Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

Author contributions

TZ: Conceptualization, Formal analysis, Funding acquisition, Investigation, Writing – original draft, Writing – review & editing. MM: Formal analysis, Validation, Writing – original draft. MA: Project administration, Supervision, Writing – review & editing. CM: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. DD: Data curation, Writing – review & editing, Investigation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1334195/full#supplementary-material

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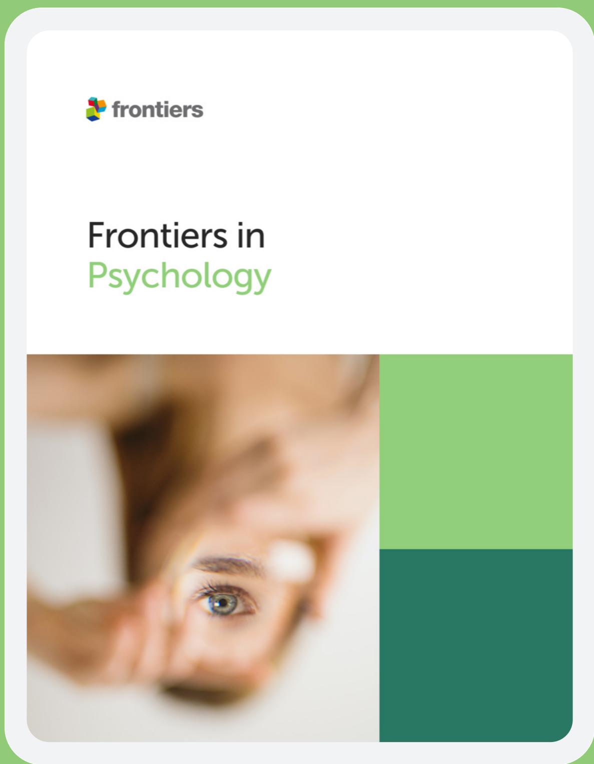

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