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SHORT REPORT

Enhancing spatial skills of preschoolers from under-resourced backgrounds: A comparison of digital app vs. concrete materials

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Abstract

Spatial skills support STEM learning and achievement. However, children from low-socioeconomic (SES) backgrounds typically lag behind their middle- and high-SES peers. We asked whether a digital educational app—designed to mirror an already successful, spatial assembly training program using concrete materials—would be as effective for facilitating spatial skills in under-resourced preschoolers as the concrete materials. Three-year-olds ($N = 61$) from under-resourced backgrounds were randomly assigned to a business-as-usual control group or to receive 5 weeks of spatial training using either concrete, tangible materials or a digital app on a tablet. The spatial puzzles used were an extension of items from the Test of Spatial Assembly (TOSA). Preschoolers were pretested and posttested on new two-dimensional (2D) TOSA trials. Results indicate that both concrete and digital spatial training increased performance on the 2D-TOSA compared to the control group. The two trainings did not statistically differ from one another suggesting that educational spatial apps may be one route to providing early foundational skills to children from under-resourced backgrounds.

KEYWORDS
digital media, education, educational app, spatial development, spatial training

Spatial skills, or the ability to mentally or physically manipulate objects and spaces in our environment, are ubiquitous. Spatial skills are recruited in everyday activities, such as getting dressed in the morning or navigating our way in unfamiliar territory. These same skills are also strongly associated with science, technology, engineering, and mathematics (STEM) achievement (e.g., Wai et al., 2009). However, children from under-resourced backgrounds generally lag behind their middle- and higher-income peers in spatial skills by age 3 (Verdine et al., 2017; Verdine et al., 2014a). It could be that children from under-resourced backgrounds are simply not exposed to enough high-quality spatial experiences. Because prior work suggests that spatial skills play a causal role in mathematics learning specifically (e.g., Bower et al., 2020; Cheng & Mix, 2014; Cheung et al., 2019; Gilligan et al., 2019; Hawes et al., 2015; Lowrie et al., 2017), providing children who have relatively lower spatial skills with spatial instruction may bolster these early foundational skills. Thus, the goal of the current study was to examine the effects of both concrete and digital spatial assembly training on spatial skills of children from under-resourced backgrounds.

Though children's spatial skills are malleable (Uttal et al., 2013), little is known about which preschool interventions optimize spatial skills. Uttal and colleagues (2013) conducted a meta-analysis to examine the effect of three types of training on spatial skills: semester-long or spatially relevant course (e.g., spatial course for engineers); video games (e.g., Tetris); and rehearsal with a spatial task (e.g., mental rotation). Results suggested that each type of training produced positive improvement in spatial skills, with no type being better than another. However, one type of contrast not yet empirically examined involves the training platform, such as the use of concrete (physical objects children can handle) or digital (images of objects represented on an electronic device) materials.

Educational technology is quickly and constantly redefining our education systems (National Association for the Education of Young

Children & Fred Rogers Center for Early Learning & Children's Media et al., 2012). For example, countries like, Rwanda, Uruguay, and Peru implemented "one laptop per child" programs. Yet, there is little empirical evidence to suggest this type of program helps children's educational achievement (e.g., Cristia et al., 2012). In the United States, entire school districts all over the country are providing children with iPads. Moreover, children are increasingly using more mobile technology, such as tablets and smartphones (Rideout & Robb, 2020). However, children from lower-income families used significantly more daily mobile media (1 h, 43 min) than their middle-income peers (59 min) and higher-income peers (40 min) (Rideout & Robb, 2020). Thus, providing high-quality spatial experiences via digital apps may be one way to bolster under-resourced children's spatial skills in early home environments.

The embodied cognition and cognitive development literature are replete with arguments about whether adults and children learn better from experience with concrete materials requiring the use of their bodies (e.g., Brown et al., 2009; Glenberg et al., 2004; Uttal et al., 1997) or equally well from experiences that do not promote physical involvement. There is additional controversy – but little research – about whether concrete materials are essential for young children's learning or whether two-dimensional, digital materials are equally potent (e.g., Clements & McMillen, 1996; Cohen et al., 2011). Researchers are also examining how children's performance on digital apps that are currently available through App stores relate to children's cognitive skills and STEM learning (Pila et al., 2019; Polinsky et al., 2021). Thus, exploring digital platforms for spatial learning may prove particularly powerful for under-resourced children whose parents—that use less child-directed language (Golinkoff et al., 2019)—may also engage in less scaffolding of their children's spatial experiences. To maximize children's learning about space, we must also probe the efficacy of instruction using concrete versus digital materials. Studies-to-date have separately examined the efficacy of spatial training with either concrete or digital materials resulting in mixed findings.

1 |

1.1 | Spatial training with concrete materials

Prior spatial training studies that successfully increased children's spatial skills have used a variety of concrete training materials, such as two-dimensional (2D) mental rotation or spatial visualization training (e.g., Cheng & Mix, 2014; Fernández-Méndez et al., 2018; Xu & LeFevre, 2016), manual mental rotation training (Wiedenbauer & Jansen-Osmann, 2008), full-body immersive perspective-taking training (Bower & Liben, 2020), or a multi-week instructional program (e.g., Lowrie et al., 2017). One particular type of spatial activity that prior spatial training interventions used successfully with younger children is concrete spatial assembly, such as tangram-like puzzles or block building (e.g., Bower et al., 2020; Casey et al., 2008; Newman et al., 2016). For example, Casey and colleagues (2008) found that teaching block-building to kindergartners not only developed their block-building skills, but transferred to performance on a similar spatial visualization task, the WISC-IV Block Design subtest. Similarly, two-dimensional spatial assembly training significantly improved preschoolers' spatial skills for children from under-resourced backgrounds (Bower et al., 2020).

RESEARCH HIGHLIGHTS

- We examined the efficacy of two spatial assembly trainings that differed in delivery (concrete materials vs. digital app) among preschoolers from under-resourced backgrounds.
- After 5 weeks of training, preschoolers in both the concrete and digital app training conditions increased their spatial skills more than a business-as-usual control group.
- The concrete and digital training conditions did not significantly differ in their improvement in spatial skills.
- Educational spatial apps--when designed with science of learning principles--may be one route to providing early foundational skills to children from under-resourced backgrounds.

During structured spatial assembly interventions, children are typically asked to create their own block construction based on a model construction. This type of spatial assembly task may be particularly effective in eliciting and bolstering young children's spatial skills. Children's ability to copy a model likely elicits spatial skills from four broad categories as conceptualized by Chatterjee (2008), Newcombe and Shipley (2015), and Uttal and colleagues (2013). For example, encoding the model construction prior to building one's own construction requires an understanding of the intrinsic-static properties of the model (e.g., size and arrangement of blocks). Examining the layout and orientations of pieces in the model construction and then trying to construct the same piece orientations in one's own construction may require extrinsic-static skills. Envisioning how the model construction might look from a different angle when trying to determine where to place a particular piece may require extrinsic-dynamic skills, such as perspective taking. Finally, visualizing changes that may improve one's construction may require intrinsic-dynamic skills, such as mental rotation.

1.2 | Spatial training with digital materials

It is possible that spatial training with digital materials may also provide similar spatial reasoning experiences. For example, Hawes and colleagues (2015) provided 6- to 8-year-olds with a 6-week two-dimensional mental rotation training on an iPad device and found significant training effects on children's mental rotation skills. Findings from other studies further support digital spatial training effects on 7- and 11-year-olds' spatial skills (e.g., Cheung et al., 2019; Mix et al., 2020). On the other hand, other studies find mixed results of digital spatial training effects on 5- and 7-year-olds' spatial skills

(Cornu et al., 2019; Gilligan et al., 2019). While less is known with younger children, a brief digital spatial training with 3- and 4-year-olds improved performance on a spatial imitation task (Subiaul et al., 2019).

Overall, concrete and digital spatial training considered separately can be effective in improving children's spatial skills, but future research is needed to better understand the mechanisms and characteristics of these training platforms that make them effective. Here, we take the first step to understanding these affordances by comparing the effectiveness of concrete and digital spatial training regimens that were virtually identical (with the exception of platform). There are several possible outcomes.

One possibility is that digital training materials may put children at a disadvantage because some argue that children's exploration of concrete objects is essential for conceptual development (Bruner, 1966; Piaget, 1970) – particularly spatial cognitive development (e.g., Wiedenbauer & Jansen-Osmann, 2008). Moreover, a media bidirectional *transfer deficit* exists among 3-year-olds as they made significantly fewer correct puzzle-piece placements using 3-dimensional objects (e.g., sliding magnetic pieces across a magnetic board) after observing an experimenter produce an action using a 2-dimensional touchscreen (e.g., sliding virtual pieces across a screen) (or vice versa) than if both the test and observation phases used the 3D magnetic board (Moser et al., 2015). As such, digital training materials could be detrimental to young children's learning.

On the other hand, Barr (2019) suggests that young children can learn from age-appropriate, well-designed media, especially when other people engage with children during digital play. Research is just beginning to explore what constitutes age-appropriate and well-designed media, such as effective educational apps (Hirsh-Pasek et al., 2015; Meyer et al., 2021), and how the effectiveness of these educational apps compare to more traditional, concrete toys and curricula. Clements and McMillen (1996) note that "computer manipulatives can be just as concrete as physical ones" (p. 271). In the current study's context, the digital manipulative is similar to the concrete manipulative with two exceptions. First, children cannot *pick-up* puzzle pieces to configure them, but instead need to *slide* pieces across a screen using one finger (or rotate pieces using two fingers). Second, a digital character scaffolds the child rather than a human. Thus, it is conceivable that one platform is just as effective as the other. Alternatively, digital spatial training may have stronger effects on children's spatial skills. Digital technology, especially the ever-changing countless mobile apps, seem to captivate young children as evidenced by their increase in daily use over the years (Rideout & Robb, 2020). This engaging and 'novelty' feature of mobile app use—when designed and used appropriately (Hirsh-Pasek et al., 2015)—could be beneficial during a spatial training that has repeated training sessions because it may help to sustain children's attention and engagement for longer periods of time.

1.3 | The current study

Given that apps are often recommended as a booster for children, we asked whether a spatial app was beneficial for children from

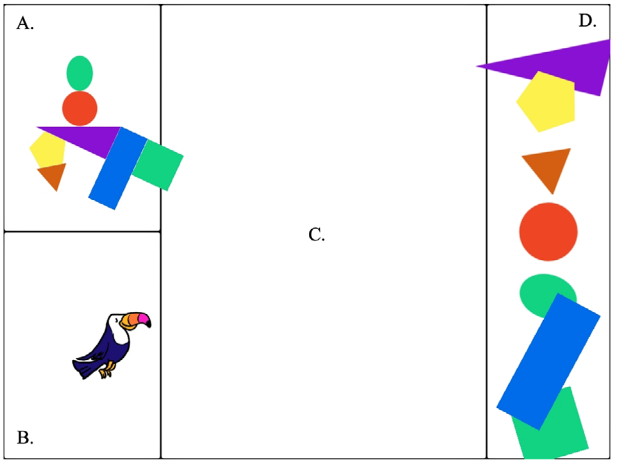

FIGURE 1 Example of a complex test trial from the app interface of the modified 2D test of spatial assembly (2D TOSA; adapted from Verdine et al., 2017). For illustrative purposes, parts of this interface are labeled: A. model to be constructed, B. "Tooki the Toucan," C. area to build puzzle, and D. available puzzle pieces. Tooki (B) asks the child to make their pieces (D) look just like the one in the picture (A). Tooki watches while the child places their pieces (C). If the child places the pieces correctly, Tooki provides positive feedback and continues with the birthday party narrative to eventually move onto the next puzzle. However, if the child is incorrect on the first attempt, then the incorrect pieces are placed back into the area D for the child to try again. If the child is incorrect on the second attempt, Tooki moves the incorrect pieces to match the model construction

under-resourced backgrounds who may engage more with digital mobile devices. The current study compares the effects of two delivery methods (concrete versus digital) of the same educational intervention on facilitating spatial skills of preschoolers from under-resourced backgrounds. The data analyzed are part of a larger intervention project (Bower et al., 2020) that examines spatial training effects with concrete, tangible materials or a digital tablet app on preschoolers' spatial skills. The intervention used a modified version of the original two-dimensional Test of Spatial Assembly (2D TOSA; Verdine et al., 2014b, 2017) as the training tool with either concrete, tangible pieces on a board or an app on a tablet. Children were asked to build a set of target constructions from models using a set of geometric pieces.

The digital app used in this study was created by our team, along with an external animation and production company (see Figure 1 for example digital interface 2D TOSA trial), for several reasons. First, we wanted to design a developmentally-appropriate app based on science of learning principles. For example, the app needed to provoke physical and mental activity; promote behavioral, emotional, and cognitive engagement; facilitate meaningful learning; and provide some form of social interaction—even if only with the app (e.g., Hirsh-Pasek et al., 2015). Second, the new app needed to directly parallel the concrete 2D TOSA.

Preschoolers from under-resourced backgrounds were randomly assigned to either 5 weeks of concrete or digital training or a 'business-as-usual' control group. We hypothesized that children who received training in either the concrete or digital formats would significantly

TABLE 1 Primary caregiver education level

Education Level	N	Percent of sample
Less than high school	4	7%
Some high school	5	9%
High school diploma or GED	11	19%
Trade or professional school	6	10%
Some college	22	38%
Associate's degree or 2-year community college	10	17%

increase their spatial skills compared to children who did not receive training. We also hypothesized there would be no significant difference between concrete or digital formats as any exposure to spatial training would be beneficial for children from under-resourced backgrounds.

2 | METHOD

2.1 | Participants

A total of 61 3-year-olds (M_{Age} = 42.90 months; *SD* = 3.09; range = 36.95 to 47.86 months; 30 females) from under-resourced backgrounds were recruited from Head Start facilities in the surrounding urban areas to participate in the current study. We defined "under-resourced" background by collecting the primary caregiver's education level: Caregivers with an associate's degree or less were considered under-resourced as education correlates with earnings (see Table 1 for a breakdown of caregiver education levels). Based on parent report, the sample was 48% Black, 17% Caucasian, 11% Asian, 11% other, and 13% unreported. Of all the children, 25% were Hispanic or Latino. All children were native English speakers. The project was approved by the institutional review boards. Children were randomly assigned to conditions: 20 children in the control group; 23 children in the concrete modeling and feedback training condition; and 18 children in the digital modeling and feedback training condition. See Table 2 for a breakdown of child characteristics by condition. Children received stickers as thanks for their participation.

2.2 | Procedure

Children were pretested (Week 1), trained (if in an experimental condition; Weeks 2–6), and posttested (Week 7) individually in a private room outside of the preschool classroom. Children in the concrete and digital 2D TOSA training conditions received five spatial training sessions (10 min each) over the course of an average of 5 weeks. Children in the business-as-usual control group stayed in their classrooms and participated in their usual classroom activities with their classmates for the 5 weeks. All participants were pre- and posttested on a 2D spatial assembly assessment (modified 2D TOSA) with different items from the training items and the Woodcock Johnson-IV Picture Vocabulary task (WJ-PV; Schrank et al., 2014). WJ-PV was included to control for the extent to which language ability contributed to spatial training effects.

2.3 | Concrete and digital 2D test of spatial assembly (2D TOSA; Verdine et al., 2017)

The 2D TOSA was modified by adding six more test trials to form two sets of six items each (Forms A and B): The set order for pre and posttest (e.g., A-B, B-A) was counterbalanced across participants as well as between concrete and digital formats. The number of puzzle pieces per trial for these testing sets each ranged from three to seven pieces (see Figure 1 for example trial). For training sessions, an additional 30 trials (six trials per each of the five training sessions) ranging from 2- to 7-piece puzzles were added to avoid having children experience the same trial more than once. The development of the digital version of the 2D TOSA took a great deal of time and was not available for administration to children in the concrete training condition as the concrete training was completed prior to the start of the digital training. Thus, the pre- and posttest of interest in the current study is

TABLE 2 Participant demographics and pretest scores by condition

		Covariates						
		Child Sex						
Condition	N	Males	Females	Mean Age in Months (SD; Range)	Mean WJ-Vocab Score (SD; Range)	Mean Pretest concrete 2D TOSA score (SD; Range)	Mean Posttest concrete 2D TOSA score (SD; Range)
Control	20	10	10	42.99 (3.38; 38.43-47.86)	14.80 (4.37; 7–21)	0.47 (0.22; .15-.86)	.47 (.21; .15-.90)
Concrete Training	23	12	11	42.99 (3.20; 36.95-47.24)	14.43 (5.71; 2–26)	0.45 (0.21; .15-.92)	.63** (.19; .28-.99)
Digital Training	18	9	9	42.68 (2.75; 37.15-47.04)	15.06 (3.99; 8–20)	0.50 (0.21; .22-.93)	.62* (.16; .35-.88)

Note: There were no significant group differences in children's mean age in months ($p = .941$); mean WJ-Vocab score ($p = .918$); nor pretest concrete 2D TOSA scores ($p = .748$). For comparisons of posttest scores with the control group as the referent.
**$p < .01$.
*$p = .050$.

the concrete 2D TOSA because it was administered to both the concrete and digital training conditions. To preemptively address the possibility that the additional digital 2D TOSA assessment influenced concrete 2D TOSA task performance for the digital training children (via testing fatigue or repeated TOSA testing), we implemented eight testing orders that were counterbalanced across participants (and within a participant's pre/posttest order). As a preliminary check, the testing order was assessed: There was no significant order effect on pretest task performance (p = .503) nor posttest performance (p = .969). Because (1) TOSA testing sets and orders were counterbalanced, and (2) testing order did not have a significant effect on task performance, the additional TOSA assessment for the digital training group was not a concern.

To keep children engaged during the training and testing, this modified 2D TOSA was transformed into a fun game guided by a birthday party narrative. The concrete version of the modified 2D TOSA required participants to recreate a picture of a design using foam cutouts of geometric shapes (see Bower et al., 2020 for more details on the testing/training apparatus). For the pre- and posttests, two practice trials and six test trials were administered. During the two practice trials, the experimenter demonstrated the task and then asked the child to "make your pieces look just like the picture." If a child failed to recreate the image successfully on their first or second attempt, the experimenter corrected the child and asked them to try again.

The comparable, digital version of the 2D TOSA (see Figure 1) was conducted using a tablet app with the equivalent design, structure, and birthday party narrative as the concrete version. Tooki the Toucan, a digital character in the app, provided the same instruction, prompts, and scaffolding the human trainer provided in the concrete format. Although the human did not have an instrumental role in the digital 2D TOSA, a human experimenter sat beside the child while the child completed the digital 2D TOSA to ensure the child was on task and the app was working properly. The only external input the human experimenter provided was during the practice trials when the experimenter needed to demonstrate how to physically move the pieces on the tablet (i.e., using one finger to slide the pieces and two fingers to rotate them).

For both the concrete and digital versions, once the two practice trials were completed, the participant moved sequentially onto the six test trials—all using different puzzle designs of increasing levels of difficulty. For the test trials, the participant did not receive any corrective feedback. For the concrete version, the participant indicated completion of each design, and the designs were photographed for later, offline coding by an experimenter. Because the digital app was equipped with a digital coding scheme that mirrored the concrete version, the app scored the finished designs in real time and the scores were exported at a later time.

Each of the six testing trials was coded for accuracy based on three dimensions (e.g., correct adjacent pieces; correct horizontal and vertical placement of pieces; and correct relative position of pieces). The mean of the correct dimensions was used as the 2D TOSA score. For more details about the coding system and trial procedure, see Verdine et al. (2017). To ensure inter-rater reliability for the coding of the 2D TOSA concrete version, 20% of participants were scored by two coders with an intraclass correlation of .99.

2.4 | Spatial skill training

The current study is part of a larger project that explores factors during the modified 2D TOSA training that best promote early spatial skills. Here, only children in the concrete modeling and feedback, digital modeling and feedback, and control conditions were analyzed. We focused on only the modeling and feedback conditions because the digital modeling and feedback training mirrored the platform of current spatial assembly or puzzle apps on the market (e.g., presenting shapes with little variety and no definitions of shape properties; Resnick et al., 2016).

2.4.1 | Concrete training

The concrete training condition used a bare-bones corrective procedure during the modified 2D TOSA training. Each training session consisted of two parts: First, children saw a shape "parade" in which the experimenter sequentially displayed the nine shapes in the following order: circle, oval, triangle, square, rectangle, kite, parallelogram, pentagon, hexagon. The shape parade was included as part of the training to introduce the variety of shapes to the child before the start of the 2D TOSA training. Second, each modified 2D TOSA training consisted of a total of 7 different designs or trials, including 1 practice trial, per session. The child had a maximum of two attempts to correctly place the puzzle pieces together to match the model design, for each of the 6 different training trials. If the puzzle pieces were placed incorrectly on the child's first attempt, the trainer would say, "I don't think this looks like the picture. Let's try this one again" and remove the incorrect pieces, placing them to the side of the board (without any additional feedback) so the child could attempt the puzzle a second time. If the puzzle was incorrect the second time, the trainer would place the pieces in the correct location, and then move onto the next puzzle.

2.4.2 | Digital training

The digital condition used the same corrective procedure and prompts as the concrete training. The only differences were 1) the training was presented on a digital tablet using an app and, 2) instead of a human trainer guiding the child through the sessions, Tooki the Toucan, a digital character, guided the child through the training and provided corrective feedback when necessary. Again, the experimenter was present to ensure the app was working properly; however, no additional prompts or information were provided.

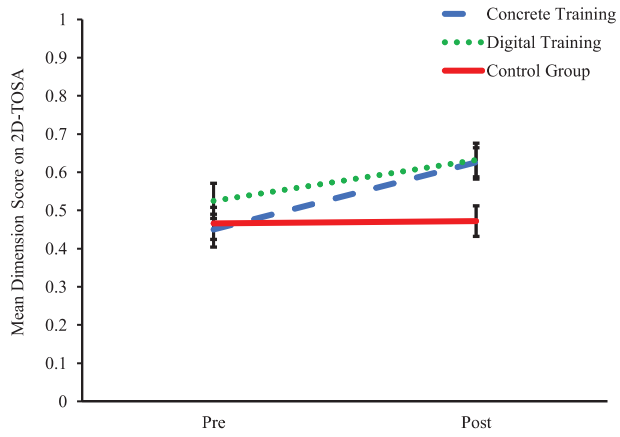

FIGURE 2 Concrete 2D TOSA training ($\beta = .40$, $p = .001$) and digital 2D TOSA training ($\beta = .29$, $p = .012$) conditions increased performance on the modified 2D TOSA skills more than the control group. The graph displays estimated marginal means when controlling for age in months, sex, and pre-vocabulary score. The errors bars represent standard errors

3 | RESULTS

3.1 | Overview

There were no pretest 2D TOSA score differences between the three groups ($p = .748$). Multiple regressions were conducted to examine the spatial training effects on 2D TOSA performance. The 2D TOSA pretest score, child characteristics (gender, age in months), and pre-vocabulary score were covariates.

3.2 | Concrete and digital training versus control group

Children who received concrete 2D TOSA training ($\beta = .40$, $p = .001$) or digital 2D TOSA training ($\beta = .29$, $p = .012$) increased their modified concrete 2D TOSA skills more than the control group (see Figure 2; see Table 3 for statistics). There is no analysis comparing performance on the digital 2D TOSA residualized change scores because the digital 2D TOSA was not administered to the concrete training children (further explanation provided in the Method).

3.3 | Concrete versus digital training

Children who received concrete training did not significantly increase their 2D TOSA performance more than children who received digital training ($p = .418$).

4 | DISCUSSION

Because spatial skills are considered a potential causal mechanism in learning mathematics (e.g., Gilligan et al., 2019; Lowrie et al., 2017; Mix et al., 2020) and possible other STEM domains (Stieff & Uttal, 2015), it is problematic that low-income children's spatial skills are lagging behind their middle- and higher-income peers (Verdine et al., 2014a). However, because children from lower-income families use more mobile media (Rideout & Robb, 2020), providing high-quality spatial experiences via digital apps may be one way to bolster under-resourced children's spatial skills in early home environments and formal educational contexts. However, it is unclear if a spatial skill training app—when developed with science of learning principles (Hirsh-Pasek et al., 2015)—can improve spatial skills, especially when compared to already established, effective concrete materials (e.g., Bower et al., 2020). Thus, the aim of the current study was to examine the effectiveness of spatial training delivered either with a digital app or concrete objects in facilitating spatial skills of preschoolers from under-resourced backgrounds.

4.1 | Concrete and digital training effectiveness compared to control group

Children who received five training sessions of either the concrete or digital spatial assembly training increased their concrete spatial assembly skills more than the control group. This finding supports prior work that also found salutary effects of spatial puzzle play and block building on spatial skills (e.g., Casey et al., 2008; Jirout & Newcombe, 2015; Verdine et al., 2014a). Moreover, these findings support the malleability of spatial skills (Uttal et al., 2013), especially for young children from under-resourced backgrounds. However, the current study extends prior work by finding that spatial assembly training on a digital app is also beneficial for spatial skills of children from under-resourced backgrounds. Even though prior work suggests that in-person social

TABLE 3 Training and format effects on spatial skills

Referent Group	Condition	*F*	*β*	*p*	R^2
Control	Concrete Training	9.95	.40	.001	.53
	Digital Training		.29	.012	
Concrete Training	Digital Training	9.95	-.09	.418	.53

Note: All regressions control for age in months, child sex, pre-WJ: Picture Vocabulary score, and pre-test score of outcome variable. All reported models have an omnibus test that is $p < .001$.

interaction is important for learning with an app (Eisen & Lillard, 2020), other research suggests that social-interactions with a digital, 'intelligent character' may also be beneficial for children's learning (Calvert et al., 2019). The current study extends this work to support the utility of social contingency in app-learning with digital characters that also interact with the human learner.

Albeit with similar stimuli (i.e., spatial assembly with various shapes), the digital training notably transferred its effects to an increase in *concrete* 2D TOSA performance. As described in the Method, only the concrete 2D TOSA was administered as a pre and posttest to children in both the concrete and digital training conditions. Digital-to-concrete and concrete-to-digital transfer is difficult for 3-year-olds (Moser et al., 2015). However, the current findings support prior work that also found similar spatial training media transfer effects (e.g., Hawes et al., 2015). Future work should examine the extent of this digital-to-concrete transfer with stimuli that vary in their similarity. Nonetheless, these results are encouraging for the promise of training with digital materials considering the children in the concrete training condition did not face the challenge of transferring training across media types.

4.2 | Digital training effectiveness compared to concrete training

There was no significant difference by training platform (concrete versus digital) on children's spatial skills. This is an encouraging finding for several reasons. First, from a theoretical perspective, past research has argued that children's exploration with concrete objects are essential for facilitating conceptual (Bruner, 1966; Piaget, 1970) and spatial (e.g., Wiedenbauer & Jansen-Osmann, 2008) development, particularly in the initial phases of learning (Fyfe et al., 2014). Exploring with manipulatives may help to ground and provide a foundation for more abstract spatial concepts. On the other hand, others argue that both concrete and imagined object manipulation are effective for learning (e.g., Glenberg et al., 2004). The current findings extend this notion and suggest that both concrete and digital toys that require some degree of manipulation (i.e., moving and assembling puzzle pieces) can be beneficial for young children from under-resourced backgrounds. Second, from an applied perspective, children's use of screen media is increasingly pervasive in daily life, especially for children from under-resourced backgrounds (Rideout & Robb, 2020). Thus, if the digital training is just as effective as the concrete training, then providing this educational spatial app for children with lower spatial skills could be one route to introducing early, high-quality spatial learning experiences.

4.3 | Limitations and future directions

One limitation of the current work is that although this is the first study to design a spatial assembly training app to mirror an already-established concrete spatial assembly training, the exact comparison between concrete and digital formats is not perfect. For example, during the digital training, children inadvertently received *nonverbal* feedback after placing each piece of the puzzle because if the piece was within a few millimeters of its correct location and orientation, it snapped into place. In both the concrete and digital training conditions, children did not receive corrective *verbal* feedback until after the child attempted the whole puzzle. Despite this small difference between formats, we believe the formats are similar enough for the direct comparisons and conclusions in the current study. Additionally, future work should assess delayed training effects to examine the training's durability.

In conclusion, the current findings suggest that a short 5-session spatial training intervention using either concrete manipulatives or an educational app developed for the current study is beneficial for spatial skills of children from under-resourced backgrounds. These findings lay the foundation for future work to explore effective spatial trainings using concrete and digital platforms to promote children's spatial skills and possible transfer to STEM learning. The accessibility and mobility of the spatial training app are attractive qualities that have potential to be far-reaching (i.e., homes, preschools, museums). However, understanding the advantages and disadvantages of this type of technology is paramount so it can be used appropriately and effectively.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from either Roberta Michnick Golinkoff or Kathy Hirsh-Pasek upon reasonable request.

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