Received: 28 December 2021 | Accepted: 15 March 2022

DOI: 10.1111/bjet.13215

ORIGINAL ARTICLE

British Journal of Educational Technology BERA

Robot programming versus block play in early childhood education: Effects on computational thinking, sequencing ability, and self-regulation

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Abstract

Programmable robotics is recently used in early childhood education (ECE) to introduce programming and computational thinking (CT) skills. However, there is a further need for research to contrast the efficacy of children's participation in robot programming and traditionally beneficial ECE activities. The present study thus investigated the effects of a robot programming intervention versus a block play program on kindergarteners' CT, sequencing ability, and self-regulation. The experiment (robot programming) versus comparison (block play) condition was randomly assigned to four kindergarten classes, which included 101 kindergarteners ($M = 64.78$ months, SD = 7.64). Statistical analyses revealed that the robot programming group ($N = 54$) had experienced greater gains over time in sequencing ability relative to those in the block play group ($N = 47$; $F = 5.09$, $p < 0.05$). Children in the robot programming group with lower level of self-regulation at baseline showed larger improvements in sequencing ability over time relative to the block play group ($F = 2.37$, $p = 0.01$). Also, children in the robot programming group with older age showed larger improvements in CT over time relative to the block play group ($F = 2.40$, $p < 0.01$). The study demonstrates the positive benefits of robot programming to early childhood development in terms of CT and sequencing ability, compared to a traditional curriculum activity in ECE—block play.

KEYWORDS

block play, computational thinking, robot programming, self-regulation, sequencing ability

Practitioner notes

What is already known about this topic

- Screen-free robot programming can enhance preschool children's computational thinking (CT).
- Block play can enhance preschool children's mathematics and executive functioning.
- Both robot programming and block play are engaging for preschool children.

What this paper adds

- An unplugged CT assessment is used to measure and compare the effects of both robot programming and block play interventions among preschool children.
- Robot programming outperforms block play in promoting children's school readiness skills such as sequencing ability.
- Children with lower self-regulation skills benefited more from the robot programming intervention.

Implications for practice and/or policy

- Robot programming and CT education should be expanded in diverse early childhood settings to boost the positive effects.
- Technology-enhanced curricula should be integrated into early childhood education.
- Teachers should receive training on robot programming in addition to more traditional skills such as scaffolding children's block play.

INTRODUCTION

Educational smart devices such as programmable robotics provide children with a playful learning experience to optimize their development in cognitive and physical abilities, social skills and emotional well-being (Dorouka et al., 2020; Kewalramani et al., 2021). Across the globe, educational policy and curricula have led to a focus on the role of computing education in promoting early childhood development (Manches & Plowman, 2017). As suggested by Wing (2008), computational thinking (CT) should be introduced from the early years of schooling to "ensure a common and solid basis of understanding and applying [these skills] for all" (p. 3720).

With technological advancements, many educational smart devices are designed with a low floor (the ability to create simple rules and/or programs without prior training), but also with high ceilings (the ability for children to express their ideas and solutions) (Bers, 2018; Papadakis et al., 2016; Portelance et al., 2016). Among those devices, programmable robotics is frequently used in early childhood education (ECE) to introduce coding, CT and sequencing ability (Bers et al., 2019; Papadakis, 2020). It offers a simple, playful and tangible way for children to develop their communication, math thinking, creativity, and social skills (Bers et al., 2019). Programmable robotics provides both tangible (ie, visual programming environment) and physical artefacts (ie, light, sound, motors) (Alimisis & Kynigos, 2009; Blikstein, 2013) which enable children to develop coding and CT skills through writing code sequences to control a robot in a certain path (Chen et al., 2017).

However, very often, educators and parents may be hesitant about whether programmable robotics should be chosen to enable children's optimal development, since many traditional activities such as block play have proven their effectiveness to stand the test of time. To our knowledge, most studies have started to study on how robot programming can be used to develop coding skills (eg, identification, sequencing) and CT among young children (eg, Bers, 2021). Yet, not much is known about the effectiveness of robot programming compared with traditional tools (eg, blocks) that are usually used by educators in STEM-related learning activities to promote children's development. As such, this study aims to address the knowledge gaps by investigating a robot programming intervention on kindergarteners' CT and sequencing ability, as well as self-regulation.

LITERATURE REVIEW

Effects of robot programming in early childhood education

Screen-free robot programming is a developmentally appropriate tool to enhance children's STEM-related cognitive abilities such as CT and sequencing ability in ECE (Bers, 2014; Çetin & Demircan, 2020; Macrides et al., 2021). Robot programming is possible to start at very early stages (at three years old) (Bers et al., 2019). Prior research has demonstrated positive effects of using educational robotics to develop other cognitive abilities especially executive functions that could facilitate children to solve and analyse problems (Arfé et al., 2019), conceive executable algorithmic procedures of their proposed solutions (Buitrago Flórez et al., 2017), enhance their working memory and inhibition skills (Di Lieto et al., 2017), as well as flexible thinking on a daily basis (Carlson et al., 2013). Moreover, robot programming could effectively promote 21st-century skills such as communication, collaboration and creativity in the classroom settings, stimulating children's critical thinking (Bers et al., 2019; Johnson, 2003; Jung & Won, 2018). In addition to cognitive ability, robot programming also promotes positive changes in learning attitudes such as motivation, confidence and interest. For example, the gamified design of robot programming could enhance students' motivation and interest, which successfully influence children to play again (Heljakka et al., 2019). Furthermore, introducing robotics and programming in early childhood serves to stimulate girls' interest and motivation in engineering fields before stereotype threat makes this more difficult in later years (Sullivan & Bers, 2019).

Robot programming uses symbolic and/or pictorial commands that require children to instruct a robot's movement and design commands in an appropriate sequence to create a series of actions (Pea & Kurland, 1984). Prior research focuses on sequencing ability through introducing CT concepts to young children. Sequencing ability is a complex cognitive ability that generate skills to arrange objects or actions in a correct order through timetable setting and procedural planning (Atance & O'Neill, 2001; Zelazo et al., 1997). To program a robot to move successfully, children need to use sequential ability to plan what happens when applying *if, next, before* and *repeat* actions, as well as procedural thinking and logical instruction to arrange robotics movement in order (Nam et al., 2019). Sequencing ability is an important skill in early childhood that facilitates students to learn about algorithms and understand the world mathematically and scientifically (Kazakoff et al., 2013). In addition, robot programming requires children to follow programming rules, social rules and children's planned procedures to solve problems with their peers. This is supported by previous research which demonstrates that children could learn to regulate one's own behaviour to conform to the coding sets' rules and social rules to output their desired programming targets (Caplovitz Barrett, 2005).

In the present study, the robot programming kit that we used is Matatalab (https://matatalab.com/) which provides students a block-based, screen-free and tangible programming environment for children aged 4 or above (Papadakis, 2020). The robot programming set allows children to control a robot through a nature map with some Bluetooth-enabled command tower, control board, wheeled robot, and coding blocks (see Figure 1). The manual coding robot offers entity modules and visual recognition to achieve simplified programming so that children can control its movement to play music and draw pictures, and play games on the map. The reason that we chose this tool is that this coding set provides solid graphical programming without a digital programming interface, which is simple and easy for children to understand and program their ideas (Lu & Pang, 2020). In addition, it is combined with chart games, painting and music for students to express and program their ideas (Lu & Pang, 2020).

Effects of block play in early childhood education

Playing with blocks has historically been a form of construction play in early childhood (Hartley et al., 1957; Hirsch, 1996; Piaget, 1962). It allows children to build spatially and represent ideas with wooden blocks to create artefacts and products. Prior research indicated

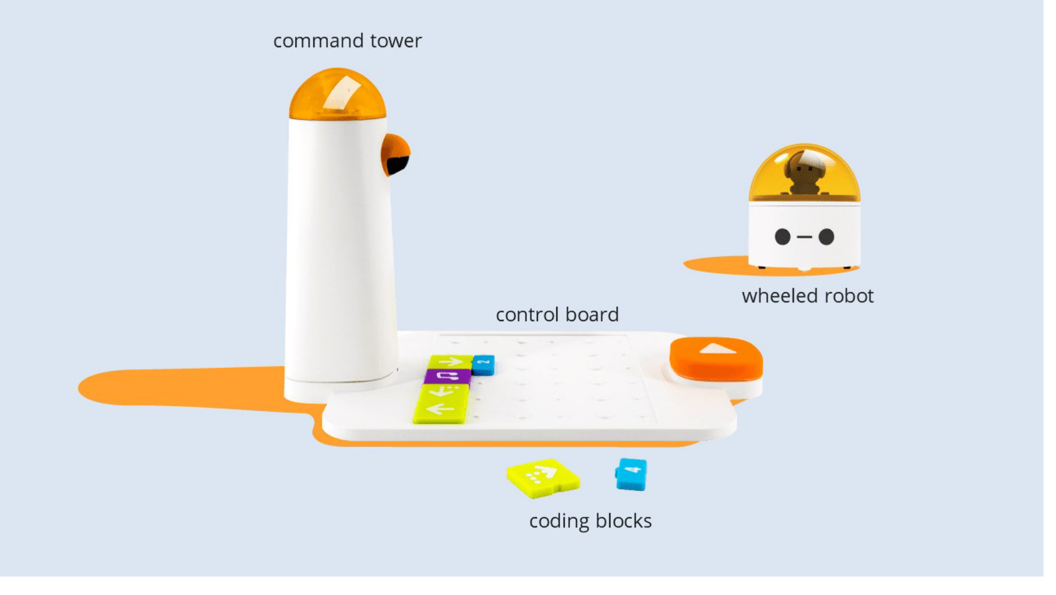

FIGURE 1 Matatalab coding set

the use of block play could effectively promote children's multiple concepts and skills such as math thinking and even CT (Schmitt et al., 2018; Trawick-Smith et al., 2017), and executive functioning such as self-regulation, flexible thinking and planning (Hanline et al., 2010). Moreover, block play aids children in developing language skills (Cohen & Uhry, 2007), creativity and imagination (Cohen & Emmons, 2017; Robbins et al., 2011), physical development and social development (Wellhousen & Kieff, 2001).

Construction open-ended play offers children the opportunity to "classify, measure, order, count, use fractions and become aware of depth, width, length, symmetry, shape and space" (p. 174) and understand concepts of space and physical properties of objects (Wolfgang et al., 2001). First, block play facilitated students to learn numeracy which includes counting, comparison, and operations (Schmitt et al., 2018). Second, researchers investigated how young children learn mathematical thinking to categorize geometric shapes, sequencing, compose a larger shape with smaller shapes and transform shapes when playing with wooden blocks (Park et al., 2008; Sarama & Clements, 2009). Third, block play could support children's CT to solve problems (Newman et al., 2021) and mathematical language development to express quantitative and spatial words (Schmitt et al., 2018). Although few researchers used block play to facilitate students to apply CT skills and practices, some researchers mentioned the potential of transferring the mathematical skills to CT abilities such as decomposing blocks, pattern recognition, step-by-step instruction and abstractions (Soleimani et al., 2016).

In addition to the association to mathematical and CT, block play in early childhood also facilitates children's development of executive functions. It offers a learning environment for children to plan the building structure, solve problems in the face of challenges and negotiate with peers (Yelland, 2011), which are important elements of self-regulation (Miyake et al., 2000). Moreover, block play could provide children with opportunities to practice mental representations of objects and products (Wolfgang et al., 2001). One of the focuses of this study is self-regulation, an important executive functioning skill to facilitate children to control their behaviour (Sniehotta, 2009) and manage their emotions to make good decisions (Fitzsimons & Bargh, 2004). Block play provides benefits for children to follow rules and work with challenges with peers. Children could learn to develop persistence and practice self-regulation to complete their planned work during block play (Hansel, 2016; Ness & Farenga, 2016).

Assessing CT in early childhood

CT is a 21st-century skill that future generations must develop, and its significance grows in ECE with the emergence of age-appropriate technologies (Kanaki & Kalogiannakis, 2018; Zhang & Nouri, 2019). CT represents a "universally applicable attitude and skill set everyone, not just computer scientists, would be eager to learn and use" (Wing, 2006, p. 33). Wing (2006) argued that CT should be added on top of reading, writing and arithmetic for educating children. Although not every child needs to become programmers, CT embraces how children interact with a computer, and approaches problem solving like a computer scientist (Zhang & Nouri, 2019).

However, there is a lack of consensus in terms of CT definition (Chen et al., 2017) and how to measure it among young children. Some recent efforts have been put into designing CT assessments for young children based on different models. First, Brennan and Resnick (2012) proposed a CT framework with three constructs including CT concepts, CT practices, and CT perspectives. Based on this framework, a computational thinking test (CTT) has been developed by Román-González et al. (2017) by using visual multiple-choice questions to detect changes in computational concepts and computational practices among young children.

This test was combined to the *Bebras Tasks* to determine to what extent children can apply their CT skills in the robot programming environment (del Olmo-Muñoz et al., 2020). Another researcher, Bers (2018), identified a series of powerful ideas (ie, algorithms, modularity, control structures, representation, hardware/software, design process, and debugging) to track and evaluate preschool children's CT skills in programming education. Based on the framework, Relkin and Bers (2019) developed a platform-specific rubric called *TACTIC* for children between five to seven years of age, which uses KIBO robots to assess children's CT abilities such as algorithms, debugging and design process. Relkin et al. (2020) further used the framework to develop an unplugged CT instrument called *TechCheck* for children aged five to nine, covering the dimensions of algorithms, modularity, control structures, representation, hardware/software and debugging.

Other than these CT assessments based on frameworks, there is research focusing on a particular platform or robotics kit. The researchers used a comprehensive evaluation such as observation, test questions, scars and artefacts to understand how children develop their CT concepts and skills in a particular programming platform (eg, Chen et al., 2017; Kanaki & Kalogianakis, 2019; Korkmaz et al., 2017; Wu et al., 2019). Among the researchers, Angeli and Valanides (2020) used Bee-Bot to assess young children's CT skills within the context of two scaffolding techniques through colour tests and spatial relation tests. Bers et al.'s (2014) study evaluated children's programming skills (debugging, correspondence, sequencing, and control flow) using TangibleK through project scores. Marinus et al. (2018) designed the Coding Development Test for children ages 3–6 years, using the robot Cubetto, which assessed how children could program the robot to go to a specified location on a mat by building programs from scratch or debugging an existing program. Children are given maximally three trials to complete the given 13 items, with more points being awarded if fewer attempts are needed. Although the authors state that the test is meant to measure CT, their assessment requires programming knowledge raising the possibility that their assessment conflates coding skills with more transferable CT skills.

Overall, the area of assessing young children's CT is still in its infancy. More research efforts should be made to design assessment methods such as knowledge tests, questionnaires and multiple-choice questions to assess children's CT in early childhood. Some of the assessments are hardware-specific that only evaluate students' CT skills on a particular platform and hardware. This exists a problem of whether these assessments could be transferred to other contexts and platforms. Furthermore, since children may not have prior coding experience and knowledge of coding, some of these coding-related CT assessments may not be appropriate for research requiring pre/post-test design. Therefore, research is warranted to identify or design age-appropriate methods to assess CT which could transfer to different contexts to solve authentic problems (Angeli & Giannakos, 2020).

In the present study, we applied a CT test drawn from the six powerful ideas (Bers, 2018) that can be transferred to diverse problem-solving contexts. Therefore, we define CT as the ability to solve problem and design solutions using the fundamental concepts of informatics (Wing, 2006), which consists of key elements such as "decomposition, abstraction, algorithm design, debugging, iteration, and generalization" (Shute et al., 2017, p. 142). This definition allows us to evaluate children's CT skills across digital and traditional learning activities. Moreover, we focused on assessing children's sequencing abilities, a subset of coding skills. We used the Picture Sequencing Task to examine if children can physically manipulate the cards to visualize the sequence of robot movement (Kazakoff & Bers, 2014). On top of this, as mentioned in previous sections, CT is related to self-monitoring and behavioural regulation in both robot programming and block play environments. Brennan and Resnick (2012) proposed that self-regulation should belong to the ability of CT perspectives. We are interested in assessing how students could enhance their self-regulation at this young age through applying Ponitz et al.'s (2008) Head-Toes-Knees-Shoulders task.

Research objectives and hypotheses

Grounded in the theoretical and empirical evidence about positive effects of robot programming experiences on CT (Bers et al., 2014; Relkin et al., 2021), sequencing ability (Kazakoff et al., 2013), and self-regulation (Arfé et al., 2019, 2020) in the early years, as well as the vital role of self-regulation in early childhood development (Diamond & Lee, 2011; Mintz et al., 2011), we compared the effects of a robot programming program versus a block play program on Chinese kindergarten children's CT, sequencing ability, and self-regulation, with the following hypotheses:

Hypothesis 1 *The robot programming intervention will enhance kindergarteners' CT (H1a), sequencing ability (H1b), and self-regulation (H1c), and show larger effect sizes relative to the comparison condition (ie, block play).*

Hypothesis 2 *Self-regulation will moderate the intervention effects on CT (H2a) and sequencing ability (H2b). Specifically, low-regulation children will be more likely to benefit from robot programming as compared to high-regulation children.*

Hypothesis 3 *Age will moderate the intervention effects on CT (H3a), sequencing ability (H3b), and self-regulation (H3c). Specifically, elder children will be more likely to benefit from robot programming as compared to younger children.*

METHODS

Participants

The present study investigated the effects of a six-week robot programming intervention on kindergarteners' CT, sequencing ability, and self-regulation. The treatment (robot programming) versus comparison (block play) condition was randomly assigned to four kindergarten classes, which included 101 preschoolers ($M = 64.78$ month, SD = 7.64) with their parents/caregivers' informed consent in terms of enrolling their child in the study. The cluster randomization resulted in two classes using the robot programming intervention, while the other two classes using the block play intervention. These child participants were enrolled in a public kindergarten in Beijing, China, serving families with a middle socioeconomic status (SES, $M = 21.39$, SD = 4.29, ranging from 8 to 29). The sample included 52 girls (51.5%), 49 boys (48.5%), 54 children in the robot programming group (53.5%), and 47 children in the block play group (46.5%). Within the sample, 93.1% of children (94 out of 101) had no prior experience in coding.

We used internationally shared protocols and procedures (Petousi & Sifaki, 2020) to seek the informed consent from participants. All the procedures used were in accordance with the 1964 Helsinki declaration and its later amendments.

The robot programming program

The intervention program for the coding classes is a curriculum designed according to the functions of the Matatalab screen-free robot (ie, Direction, Function, Loop, Artist Add-On, Musician Add-On, etc.). In each activity, 20–30 children were involved simultaneously, with 4–5 children per group in small-group activities. A total of 7 robot kits were provided for use during the collective inquiry activities. Figure 2 shows how children were engaged in using Matatalab robot for coding. In this curriculum, the powerful ideas about coding include:

FIGURE 2 Child engagement in the robot programming activities

1. Correspondence: A command corresponds to a corresponding action of the robot;
2. Algorithms: The robot moves step by step according to the sequence of the command blocks;
3. Problem decomposition: Children learn how to break down the task of drawing a square (forward/turn) and complete the task using the learnt commands and movements of the robot; and
4. Pattern recognition: Understand the placement rules for loop blocks (start loop—motion instructions—end loop), understand that loop blocks come in pairs and need to be used with number blocks.

Teacher training

The teacher training involves three parts: tool training, lesson design training and implementation strategy training. Tool training was mainly to help teachers understand how to use Matatalab, its functions that can be used in curriculum design, and possible problems that may occur. After getting familiar with Matatalab, the researchers firstly designed a sample lesson plan with the theme of "celebration dance party" for teachers as a reference. Then, teachers were asked to design and review appropriate lesson plans according to the actual situation of their children and the implementation of each activity, with researchers giving instructions and suggestions. Implementation strategy training was then conducted through observing teachers in class by the researchers. After every class, the researchers helped teachers to constantly adjust the design of the curriculum by giving suggestions for improvement, such as the grouping arrangement, learning evaluation, and how to effectively facilitate children's engagement in programming activities.

Classroom environment

Children's programming activities were taken place in the empty space of either the activity room or sleeping room of the assigned classes. In each class, the children were divided into five groups, and each group of children would use an average of 2–3 square meters of area. The activity rooms and sleeping rooms have sufficient space, good light and a quiet environment, suitable for conducting programming activities.

Implementation fidelity

In order to ensure the fidelity of the programming curriculum implementation, the researchers made the following efforts:

1. Selection of programming tools: Matatalab screen-free programming robot was used in this study, which is characterized by visual programming process, zero screen time, childlike fun design, rich functions, and real design cantered on CT. The tool is suitable for kindergarten children.
2. Preparation of the curriculum plan: The prototype of the intervention plan in this study was jointly designed and repeatedly modified by multiple researchers. The program was designed according to children's learning characteristics and Matatalab's functions.
3. Development of teachers' abilities: Prior to the intervention, researchers and teachers discussed the lesson plan repeatedly. In the process of implementation, researchers observed in the programming activities every week to help make suggestions for improvement. After each activity, teachers were organized to have reflections and make plans for improvement in the next activity.
4. Adequacy of the intervention: This study intervened children not only through the form of collective inquiry activities, but also with the help of learning-centre activities. It was ensured that there were two collective inquiry activities and several learning-centre activities every week, with each activity having the guidance of teachers to ensure children's understanding and progress.

The block play program

The comparison classes in this study adopted another intervention program about block play. This block play program enabled the comparison classes to implement construction activities via building blocks. These block play activities were mainly conducted in the construction area in each classroom. Neither programming nor robotics elements are provided in this block play program. Figure 3 shows how children were engaged in the block play program in the two comparison classes.

Teacher training

The teacher training of comparison classes includes two parts: the intervention tool training and guidance strategy training. The tool training was conducted by the researchers to show

FIGURE 3 Child engagement in the block play activities

the use of marble run blocks and guide the teachers to design diversified use schemes. The guidance strategy training involved how to guide children to use marble run blocks with goals, to think deeply, to solve problems, and to cooperate in groups.

Classroom environment

The block play program was mainly implemented in the construction area in each classroom. Each activity could accommodate 4–5 children, and the space was sufficient for children to build the blocks.

Implementation fidelity

In order to ensure the smooth implementation of the block play program, the researchers made the following efforts:

1. Identification of intervention tools: After careful research, the researchers decided to use the “marble run” as the block building tool, because it can lead children to think creatively, conduct cooperation, solve problems in depth, and allows children to experience the process of constantly adjusting solutions until the problems are solved (Wellhousen & Kieff, 2001). The intervention theme

was designed by teachers under the guidance of researchers. Each activity was constantly adjusted based on the summarized problems of the previous activities before arriving at the final plan.

2. Improvement of teachers' abilities: Besides training, the researcher provided teachers with observable record sheets to help them observe children's block play purposefully and to guide them to make reflections constantly until finding the best intervention plan and achieving the best intervention effect.

Procedure

All the participating children were assessed immediately before and after the intervention. Table 1 shows the learning activities conducted with the robot programming and block play groups respectively. One to two big-group learning activities were conducted by the class teachers to code robots or build blocks with their children every week. Six trained graduate students majoring in ECE, who were blinded to the treatment situations, administered the tests individually with the children. In the pre- and post-tests, *TechCheck* (Relkin et al., 2020) was used to assess children's CT. The Picture Sequencing Task (Kazakoff & Bers, 2014) was applied to examine if they can physically manipulate the cards to visualize the sequence of stories. The Head-Toes-Knees-Shoulders test (Ponitz et al., 2008) was used to measure children's behavioural regulation.

Measures

Demographic questionnaire

The demographic survey included parental educational attainment (high school and below, associate degree, bachelor's degree, master's degree), parental vocational status (stay-at-home or unemployed, semi-technical and technical worker, semi-professional and public servant, professional and officer, and high-level professional and administrator) and household income. The questionnaire also collects data on the child's age and gender.

Computational thinking

We used the *TechCheck* to assess young children's CT skills (Relkin et al., 2020). In this study, *TechCheck* was converted to a digital version on *Wenjuanxing,* an online surveys platform widely used in China. There are a total of 15 items focusing on six categories of developmentally appropriate CT concepts for young children: algorithms, modularity, control structures, representation, hardware/software, and debugging (Bers, 2021). According to Bers (2021), algorithm design involves a series of ordered steps taken to achieve a goal. Therefore, sequencing is the prerequisite for a successful algorithm. However, CT differs from sequencing ability due to other organic components. For example, modularity is the ability to break down complex tasks into smaller steps and manageable units (Bers, 2021). Also, debugging is required to fix errors in a program using skills such as testing, logical thinking, and iteration (Bers, 2021). Sample items include “Which works the most like a computer?” and “This seesaw isn't going up and down. How can it be changed so it works?” (See Appendix 1). More sample items can be found from Relkin et al.'s (2020) article (p. 494–495). *TechCheck* has good psychometric properties (The observed $\alpha = 0.68$; criterion

TABLE 1 Activities in the robot programming program versus the block play program

Age group	Robot programming		Block play	
	Activity	Objective	Activity	Objective
4–5 years	Hello, MatataBot	Know about MatataBot and its directional command functions	Understand the marble run	Be able to understand what marble run building block is by observing objects and watching videos
	Move forward, MatataBot	Know about and use the forward and backward command blocks	Marbles rolling down	Learn about simple building approaches
	Recognize left-turn and right-turn coding blocks	Know about and use the turn-left and turn-right command blocks	Marble tower	Be able to build the tower with multiple building blocks
	Obstacles, MatataBot	Use MatataBot's directional command functions (forward, backward, turn left, turn right)	Build freely	Be able to build the track of marbles freely
	MatataBot and parameters	Know about MatataBot's parameter function	Build cooperatively	Be able to work cooperatively to design or build relatively complex structures with reference to drawings
	The use of parameter coding blocks on the map	Use MatataBot's parameter function	I say you build	Be able to conduct creative games according to the instructions or requirements of teachers or peers to increase the game difficulty
	MatataBot draws	Know about MatataBot's drawing function	Build with creativity	Make comprehensive use of previous experience to design simple/medium/difficult levels of structures with peers and can choose to construct them on their own
	Decorate MatataBot	Decorate the MatataBot as you like		
	MatataBot dances	Use MatataBot's parameter function and directional command functions		

TABLE 1 Continued

Age group	Robot programming		Block play	
	Activity	**Objective**	**Activity**	**Objective**
5–6 years	Hello, MatataBot	Know about the MatataBot and its directional command functions	Same as above	
	Pick fruit	Use directional command functions		
	MatataBot tiny race car	Know about the parameter function		
	MatataBot passes through the games	Use the parameter function		
	Write number “2”	Know about MatataBot's drawing function		
	Draw a square together	Use MatataBot's drawing function		
	Use loops to complete tasks	Know about MatataBot's loop function		
	Celebration dance party	Use MatataBot's loop function		

Note: The same block play program was used for both age groups.

validity at $r = 0.53$) as shown in a validation study and normally takes 12 min to administer in kindergarten children (Relkin et al., 2020).

Sequencing ability

Computer programming is considered as the process of designing sequenced commands to instruct computers and robots by creating numerical sequences and/or geometric patterns (Kazakoff & Bers, 2014). To evaluate children's early coding skills, we used the Picture Sequencing Task (PST) to examine if children can physically manipulate the cards to visualize the sequence of stories. The PST was adapted by Kazakoff and Bers (2014) from Baron-Cohen et al. (1986)'s picture sequencing cards for preschool and kindergarten children. There are four picture cards in each of the picture stories in which children were asked to place them in the right order to construct a complete story. Researchers first showed and explained the cards to the children about the picture sequencing tasks according to the standardized procedure. After administration of each sequencing task, the researchers marked each participant's performance with a score of 2, 1, or 0 for a correct sequence, a sequence with the correct beginning and ending cards, and a completely incorrect sequence respectively. Five picture stories were used for the pre-test and the other five for the post-test. As such, we obtained a total score of 0 to 10 points for the PST for each child participant. The categories of picture stories used for the pre- and post-tests were matched to ensure equal difficulty for both tasks.

Self-regulation

We used a direct measure of behavioural regulation—*Head-Toes-Knees-Shoulders* (HTKS) to assess children's self-regulation behaviours, consisting of three organic components: inhibitory control, attentional flexibility, and working memory (Ponitz et al., 2009). The HTKS task is usually administered in three phases (Ponitz et al., 2009): firstly, children are asked to respond naturally to two commands (eg, “touch your head” and “touch your toes”). Secondly, children are asked to do the opposite of the original instruction. Lastly, the researchers provide additional rules to increase cognitive complexity. The HTKS consists of 30 items, with a score ranging from 0 to 60. Researchers then marked each participant's performance 0 point for wrong responses, 1 point for self-corrected responses, and 2 points for correct responses. Such measure has a high interrater reliability ($\kappa > 0.90$) and validity in assessing behavioural self-regulation of children from diverse cultures in previous studies (eg, McClelland et al., 2007; von Suchodoletz et al., 2013; Wanless et al., 2011) and show its suitability for young children's assessments (Schmitt et al., 2018).

Statistical analyses

First, we addressed the missing responses (1.22% of the total responses) in the dataset. To deal with this issue, existing literature has recommended to use the multiple imputation strategy to settle with the missing responses in the specified dataset (Baraldi & Enders, 2010; Enders, 2010). In this way, we carried out 100 imputations which yielded 100 imputed datasets. Second, independent t tests were conducted to compare groups at baseline. Third, one-way Analysis of Covariance (ANCOVA) tests were conducted with the baseline scores entered as covariates to assess for group by time interactions. Due to the exploratory nature and the relatively small sample size in this study, we conducted both formal significance testing (using ANCOVAs and *t* tests) as well as generated effect sizes reflecting group differences. We calculated Cohen's *d* using pooled pre- and post-test standard deviations (Cohen, 1988). Between-groups effect sizes were computed as the difference between within-group by *d*s (Becker, 1988). Finally, we assessed individual differences in response to the interventions using two-way Analysis of Variance (ANOVA) models to construct baseline examination with group interactions as a predictor of change. All the statistical analyses were conducted via the IBM SPSS Version 27 software.

RESULTS

There were no significant differences on the demographic variables (ie, age, gender, and family SES) and children's abilities assessed at baseline (ie, *TechCheck*, PST, and HTKS; $p > 0.05$). Results from all ANCOVA analyses, group means, and SDs are presented in Table 2. The results indicated that there was a significant group by time interaction for PST total score, $F(1, 98) = 5.09$, $p < 0.05$, after controlling for baseline levels.

Effects on CT, sequencing ability, and self-regulation

A One-way ANCOVA was conducted to determine a statistically significant difference between groups on the post-test *TechCheck* score, PST score, and HTKS score controlling for the pre-test scores respectively. Based on the results of ANCOVA, there was non-significant difference in CT between two groups, $F(1, 98) = 0.41$, $p > 0.05$. Also, the results revealed that there was non-significant difference in HTKS between two groups, $F(1, 98) = 2.62$, $p > 0.05$. However, there is a significant effect of grouping on post-test PST score after controlling for pre-test PST score, $F(1, 98) = 5.09$, $p < 0.05$.

Moderator of treatment effect

Moderators of the treatment effect were tested with two-way ANOVA, using change in CT and sequencing ability as the dependent variable. In these models, the baseline level of self-regulation significantly interacted with group to predict change in sequencing ability, $F(20, 41) = 2.37$, $p < 0.05$ (see Figure 4). Age also interacted with group to predict change in CT, $F(16, 61) = 2.39$, $p < 0.01$ (see Figure 5). No other significant interactions were found ($p > 0.05$). Children in the robot programming group with lower level of self-regulation at baseline showed larger improvements in sequencing ability over time relative to the block play group. Children in the robot programming group with older age showed larger improvements in CT over time relative to the block play group.

DISCUSSION

This experimental study investigated and compared the benefits of implementing a robot programming curriculum versus a block play curriculum in natural early childhood classroom settings. Supporting Hypothesis 1, results indicated greater improvements in response to the robot programming intervention across various outcomes relative to block play (see effect sizes in Table 2), especially in sequencing ability—a strong predictor of early coding

TABLE 2 Pre-test and post-test scores by group and assessment

Variable	Robot programming group				Comparison—block play group				Between-group Cohen's *d*	*F*	*p*
	n	Pre-test *M* (SD)	Post-test *M* (SD)	Within-group Cohen's *d*	*n*	Pre-test *M* (SD)	Post-test *M* (SD)	Within-group Cohen's *d*			
TechCheck	54	7.48 (2.80)	9.24 (2.91)	0.72	47	7.46 (2.92)	8.94 (2.86)	0.62	0.10	0.407	0.525
PST	54	4.69 (2.87)	6.37 (2.78)	0.59	47	4.26 (2.60)	5.00 (3.03)	0.25	0.33	5.090	0.026**
HTKS	54	43.2 (11.8)	49.9 (9.58)	0.69	47	39.8 (15.9)	45.3 (12.9)	0.40	0.28	2.624	0.108

Note: PST, picture sequencing test; HTKS, head-toes-knees-shoulders (HTKS) measure of self-regulation. Between-group Cohen's d = differences (Robot programming minus comparison group) between within-group pre/post *ds*; F = value of group by time interaction.

$^{**}p < 0.05$.

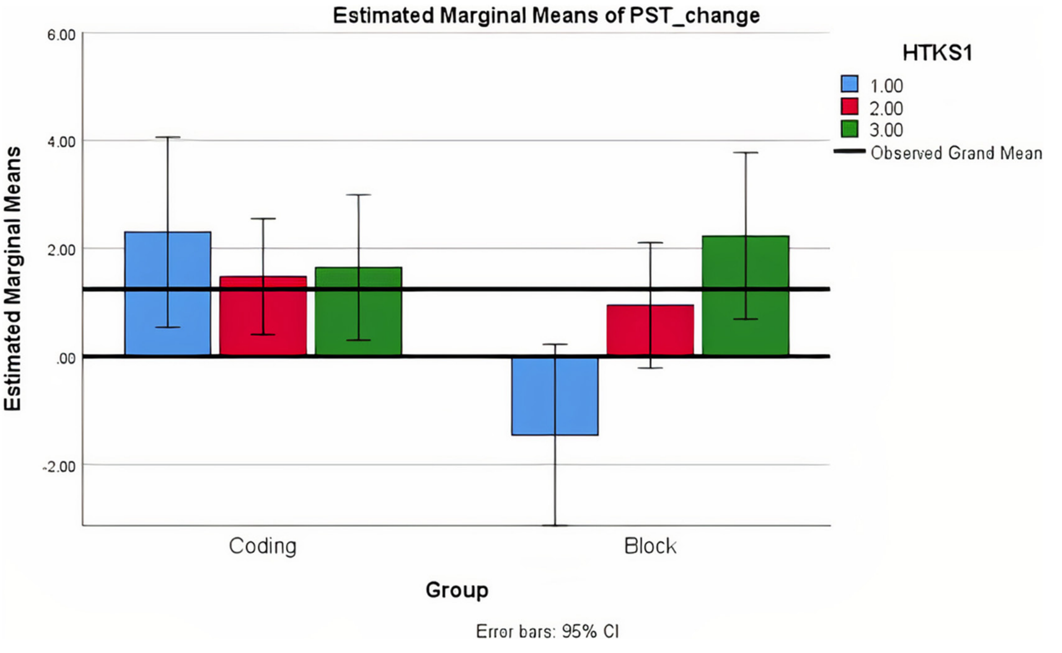

FIGURE 4 The moderating effect of HTKS at baseline in the relationship between group and PST change. The HTKS score was divided into three groups: bottom quartile, middle half, and top quartile. Quartiles were computed for display purposes only. Baseline self-regulation (HTKS score) predicts change (post/pre) in sequencing ability (PST score). Mean change in PST score is displayed separately for the robot programming group and the block play group. Children in the robot programming group with lower level of self-regulation at baseline showed larger improvements in sequencing ability over time relative to the block play group. Interaction significant at $p < 0.05$

skills (Bers, 2021). However, there was non-significant difference in CT between the two groups. The possible reason is because of the difference between CT and sequencing ability. In fact, sequencing ability is a prerequisite for algorithm design, which is a component involved in CT; however, CT differs from sequencing ability with other organic components such as modularity and debugging. Enhancing children's overall CT may be more time-consuming than enhancing their sequencing ability. Moreover, the small sample size may limit the chance to detect the small effect in this experiment.

It is worth noting that, both groups of children showed improvements in the outcomes assessed in this study over time, possibly due to the positive effects of both intervention programs and children's maturational growth. However, due to the practical problems with variable control in the present educational experiment, it is inconclusive whether block play would outperform a zero-intervention control group. Also, although our examination of effect sizes lends support to a general pattern of growth favouring the robot programming group, not all three dependent variables were significant in the omnibus test of the group by time intervention. This, as a matter of fact, highlights the need for larger samples in future intervention studies.

Notably, children in the robot programming group with lower level of self-regulation at baseline showed larger improvements in sequencing ability over time relative to the block play group ($F = 2.37$, $p = 0.01$), thus supporting Hypothesis 2b. This finding confirms the encouraging pattern of differential treatment effects that children with lower baseline functioning would show larger gains (eg, Bierman et al., 2008; Diamond & Lee, 2011; Flook et al., 2015). For instance, previous evidence revealed that baseline self-regulation would moderate treatment effects with children who received a mindfulness-based kindness curriculum (Flook et al., 2015).

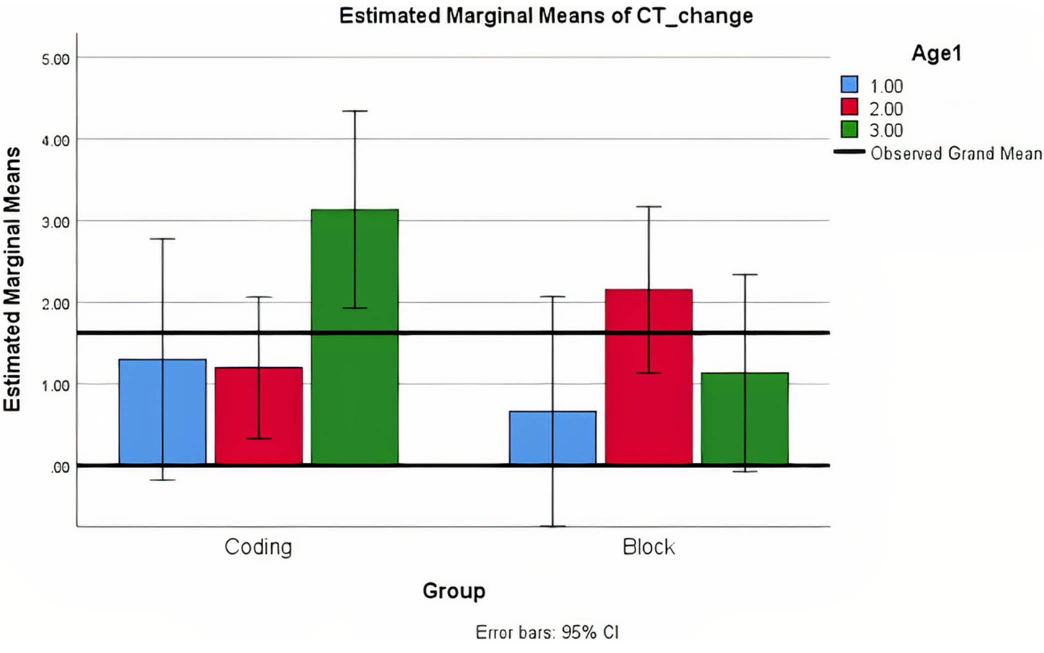

FIGURE 5 The moderating effect of child age in the relationship between group and TechCheck change. The age of children was divided into three groups: bottom quartile, middle half, and top quartile. Quartiles were computed for display purposes only. Child age predicts change (post/pre) in computational thinking (*TechCheck* score). Mean change in *TechCheck* score is displayed separately for the robot programming group and the block play group. Children in the robot programming group with older age showed larger improvements in CT over time relative to the block play group. Interaction significant at $p < 0.01$

Also, children in the robot programming group with older age showed larger improvements in CT over time relative to the block play group ($F = 2.40$, $p < 0.01$), thus supporting Hypothesis 3a. This finding helps to understand differences in how individuals respond to intervention regarding the developmental benefits. It might support those older children in the early years may be more capable to absorb the powerful ideas of coding and CT when learning how to code. This may be explained by the fact that block play has a lower floor than robot programming for young children, at least for the Matatalab coding set used in this study. As compared to block play, a robot programming set such as Matatalab may bring more barriers to learning to code such as getting used to the characteristics of the robot and the rules for coding, which deserves more in-depth examination. This issue may apply to other programmable robots suitable for young children, such as KIBO (Bers et al., 2019) and Cubetto (Anzoátegui et al., 2017).

Taken together, the findings from this study suggest that there are benefits for a general ECE classroom and that children with delays in self-regulation may experience additional gains. Older children may also benefit more from the robot programming program as they may be readier for using the robot programming materials regarding the cognitive skills and fine motor skills. Since children need to follow rules and CT concepts to make patterns, they need self-regulation to repeat the steps and rules in robot programming activities. They may help understand why self-regulation and age moderated the efficacy of coding interventions in kindergarteners. Last but not least, these positive changes were found after a modest intervention dose in a short intervention period (ie, six weeks), thus supporting the practicality of the robot programming approach in ECE settings. As such, this intervention is an accessible and cost-effective strategy to promote CT and coding skills in screen-free and robot programming experiences in addition to more traditional ones such as block play. Scaling up this kind of innovative curricula with digital technologies may set children on a trajectory for positive development, especially in the fields of STEM.

Contributions and implications

The present study makes the methodological contribution by using an unplugged CT assessment (ie, *TechCheck*), as well as a pretest-posttest randomized experimental design, to measure and compare the effects of robot programming versus block play interventions among preschool children. Previous studies, however, tended to use CT assessments requiring children's prior programming experience (eg, Bers et al., 2014, 2019), thus limiting the possibility of evaluating the impact of traditional learning experiences on CT outcomes. This study, therefore, moves forward our understanding regarding the effects of digital versus traditional learning programs on the development of children's CT in the early years. This will inspire more researchers to use similar methodologies for digital learning program evaluation.

Theoretically, this study provides an evidence-based argument that digital learning programs such as age-appropriate robot programming activities can outperform traditional learning activities such as block play in promoting children's school readiness skills (eg, sequencing ability). Therefore, this study sets a solid foundation for the future research on and practice of technology-enabled learning programs in ECE settings. More specific implications can be drawn upon the findings of this experimental study, as follows.

First, the present study provides solid evidence for promoting positive digital learning experiences in ECE. In the past, there are a lot of controversies about the necessity of integrating coding into ECE due to the well-documented benefits of traditional pedagogical activities such as block play. Our research shows that digital learning which encourages creativity and self-regulation, eg, coding with developmentally appropriate tools, can lay a solid foundation for young children's school readiness such as sequencing ability and CT.

Second, robot programming curriculum outperforms a more traditional integrated STEM learning program—block play (Lin et al., 2021)—for improving their CT and coding skills which are vital in the 21st century. Our research demonstrates the power of interactive technology for promoting early learning and development. As situated in real-world classroom settings, this study lends support to a technology-enhanced curriculum reform in ECE settings. Teachers should receive training on robot programming in addition to more traditional skills such as scaffolding children's block play.

Third, our observations demonstrated that positive digital learning experiences promoted for young children should be based on their intrinsic motivation; yet the effects of culturally responsive pedagogy remain to be examined with an experimental design (eg, culturally responsive pedagogy versus game-based learning for integrating robot programming into ECE).

Limitations and future research directions

There are several limitations in the present study. First, *TechCheck* may not be sensitive for age 4 (Relkin et al., 2020), leading to the inconclusive result regarding the moderating effect of age. At the moment of this study being conducted, *TechCheck*-K was not yet available (Relkin & Bers, 2021). Further studies with younger age should adopt the *TechCheck*-K or even other instruments (eg, BCTt, Zapata-Cáceres et al., 2020) for measuring the emerging CT among very young children. Examination of the intervention effects would be augmented by incorporating other measures such as third-party observations of classroom behaviours and qualitative data such as children's perspectives reflected in their artifacts and voices.

Second, the sample size may not be large enough for detecting very small effects in terms of improvements in HTKS. Theoretically, robot programming can promote self-regulation. Examination of effect sizes in the current study also favoured the robot programming group on the measure of self-regulation (HTKS) relative to the block play group, although the difference between groups was non-significant based on the one-way ANCOVA result. In the future, a larger sample size with a more rigorous research design such as Randomized Controlled Trail (RCT) is warranted to reveal the effect of early coding education programs on young children's self-regulation skills. Also, due to the small number of classes, we cannot identify the potential confounding effect of class grouping. In the future, the research design of large-scale cluster RCT can be used to detect or control the class grouping effect.

Lastly, also due to a relatively small sample size, this study only employs a pre-post experimental design without following up to assess longer-term effects of interventions. In the future, three or more waves of child assessment can be considered to more rigorously assess the effects of robot programming and block play interventions in a longer run.

CONCLUSION

The study demonstrates the positive benefits of robot programming to early childhood development in terms of CT and sequencing ability, compared to a traditional curriculum activity in ECE—block play. Our findings suggest that a six-week coding curriculum with the support of programmable robotics can be age-appropriate for kindergarteners and enhance their early coding skills and CT. Furthermore, the robot programming curriculum can lead to larger gains among children with poorer baseline function (eg, lower self-regulation). Still, further work is required on the integration of tangible and theoretically sound technologies into ECE curricula for enriching the early learning experiences among “digital natives” (Bennett et al., 2008, p. 775). Our findings shed light on the vital role of innovative technology-enhanced learning programs on promoting early development, which would be important for the wellbeing of both individuals and the society.

ACKNOWLEDGEMENTS
The authors would like to thank the children and teachers who have participated in this study.

CONFLICTS OF INTEREST
The authors have no conflicts of interest to disclose.

ETHICS STATEMENT
All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was also obtained from all individual participants included in the research.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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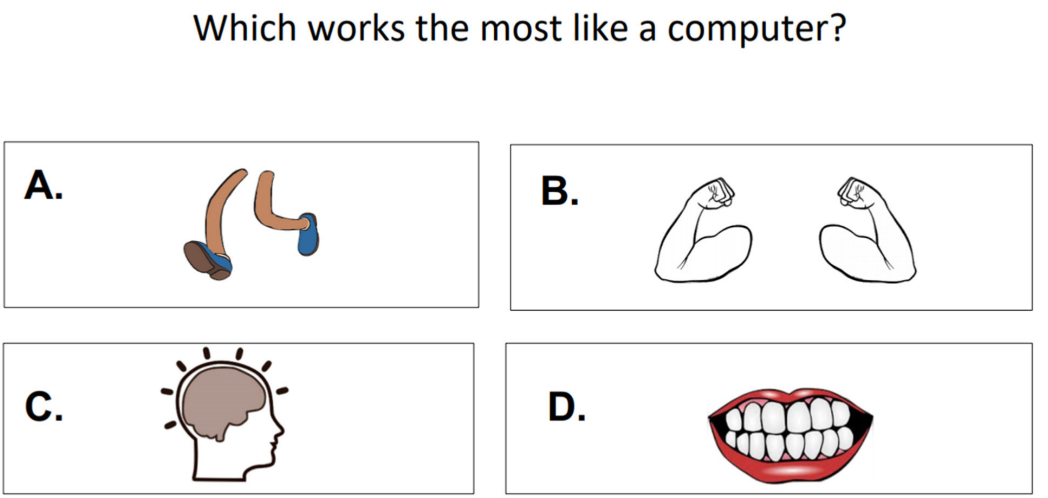
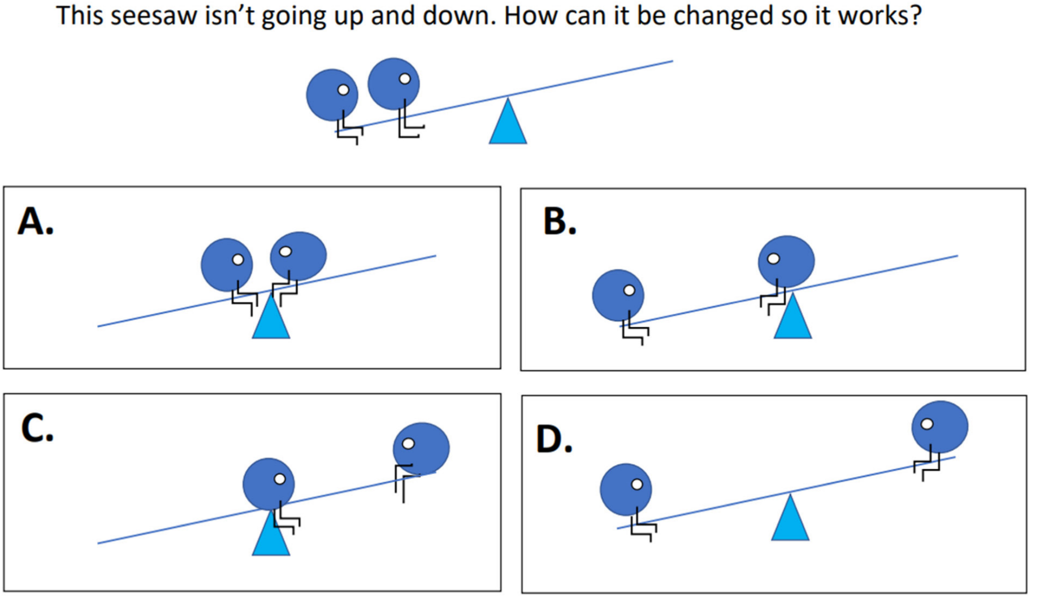
How to cite this article: Yang, W., Ng, D. T. K., & Gao, H. (2022). Robot programming versus block play in early childhood education: Effects on computational thinking, sequencing ability, and self-regulation. *British Journal of Educational Technology*, *53*, 1817–1841. https://doi.org/10.1111/bjet.13215

APPENDIX 1

TechCheck sample items (Relkin et al., 2020)





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