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Computational thinking tools for early years education: a design study

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Abstract
Computational Thinking (CT) is recognised as an essential foundational skill that enhances problem-solving abilities and is a crucial learning area for effective engagement in an increasingly digital society. This paper highlights the significance of screen-less tangible tools in promoting young children's exploration and open-ended play with technology and their exposure to CT, which adults can further support. It presents a design-led investigation involving 16 children (approximately 18 to 36 months old) and their caregivers, examining their interactions with a novel digital technology probe, 'Embeddables.' We aimed to explore how new types of interactions in CT tools can be developed to embody CT experiences in diverse ways. The Embeddable probes are multi-modal plush tools that respond when proximally to each other. In our study, we introduced Embeddables at an Australian children's museum to observe how young children engaged with them. Our analysis highlights the features of the CT technology probes that foster new opportunities for social and open-ended play, paving the way for digitally enhanced experiences that embody Computational Thinking and related skills. Our discussion revolves around the potential for CT with young children in playful environments, focusing on how the design features of tools facilitate this process.

Keywords Children · Early years education · Computational thinking · Tangible · Play · Design

1 Introduction

The introduction of computational thinking (CT) in early childhood education is seen to be developmentally important for gaining skills in problem-solving and reasoning, with potential foundations for computer programming (Bers et al., 2022; Wing, 2006). The contextualised application of these skills promotes learning

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opportunities in computer science and, more broadly, children's engagement in everyday activities (i.e. formulating procedures, navigating maps, issuing instructions) (Bati, 2022; Education Services Australia, 2019; Wing, 2006, 2008). CT tangible tools often enhance and make CT experiences salient for young children, providing avenues for children to explore and construct knowledge (Ackermann, 2001; Papert, 2020). For young children (ages 1.5–5 years), CT tangible tools are often non-screen-based due to age development (Sullivan & Strawhacker, 2021), resemble familiar traditional toys, and are digitally-enhanced physical forms (tangible) that allow children opportunities for familiarisation and experimentation. Play-based forms and activities that encourage exploration and imagination are developmentally important for young children (Montessori, 2004; Resnick et al., 1998; Vygotsky, 2004). To date, few situated studies have investigated age-appropriate screenless CT tangible tools (Sullivan & Strawhacker, 2021), either through guided play (with adults or peers) or free play (without adult direction) (Hewes, 2006), with some notable exceptions (Bers et al., 2019; Bowen et al., 2022; Odgaard, 2022).

Studies focusing on play with CT tools have primarily concentrated on block-based or vehicle robotics with or without coding blocks and tiles (Bakala et al., 2021; Bati, 2022; Yu & Roque, 2019; Yu et al., 2020). These are often incorporated into a formalised learning maze problem-solving activity that imitates a simple CT process. Although vehicular CT tangible tools such as Cubetto and Bee-Bots (Bowen et al., 2022) are well-regarded in education research for children aged 4–8 years, our research indicates that they may not be developmentally appropriate for young children, and very little is known about how other types of digital CT tools might provide fundamental informal learning opportunities for younger children (18 – 36 months) through more open-ended play (Bird & Edwards, 2015; Kotsopoulos et al., 2022; Yu & Roque, 2019).

This paper presents a design-led process to explore tangible interaction possibilities for CT tools to build fundamental skills in CT for very young children (ages 18—36 months) in play-based environments such as children's museums. Our research question is:

> RQ: How do young children and parents incorporate computational thinking in play with novel digital tools, and what design features from the novel probe facilitated CT experiences (i.e. symbolic reasoning, procedural problem solving)?

The outcome of this study contributes to our more extensive research project focused on the effective use of Computational Thinking tools in early childhood environments that considers contextual factors such as teacher input, social environments, and peer learning. Given this age group's lack of readily available CT digital tools, a novel technology probe was built (*ISTE Standards*, 2024; Wing, 2006). We designed the novel technology probe as 1) an interactional contrast to other CT tools that are readily available, such as blocks and vehicle-based CT tools (Yu & Roque, 2019), 2) a distributed (social) system that proposes 'proximity reactions' as a method of exploring simple coding relations for young children, 3) a digital tool that can be used and played with by young children, and 4) a tool that affords activities to be scaffolded during its use. The novel technology probe—Embeddables, are character-type tools such as traditional teddy bears and dolls, in which technologies have been implanted to allow for additional physical interactions such as cuddling, throwing and multi-directional movement rather than typically afforded interactions such as pushing, pulling, sliding, and crashing, as is the case with vehicular tools. Therefore, our initial investigations centre less on learning outcomes and more on the possibilities of what these different types of interactions could offer in the way of encouraging playful interactions with the purpose of scaffolding the fundamentals of CT.

2 related work

Several recent systematic reviews have examined tangible kits and tools for developing computational thinking in children under the age of five (Bakala et al., 2021; Bati, 2022; Macrides et al., 2022; Su & Yang, 2023; Yu & Roque, 2019). These reviews reveal that while researchers concur on the significance of early exposure to Computational Thinking (CT) skills for child development, only a few studies explore the kinds of interface interactions and, consequently, non-screen-based tools that would best facilitate social interactions between children and their educators or parents (Bakala et al., 2021; Macrides et al., 2022).

At the outset, we acknowledge competing conceptions of computational thinking, with some researchers taking a narrower approach describing CT in terms of algorithmic processes (e.g., Lee et al., 2022) and others adopting a more holistic view of CT (Grover & Pea, 2013). In this paper, we use Wing's (2006) definition of computational thinking, which "involves solving problems, designing systems, and understanding human behaviour by drawing on concepts fundamental to computer science" and are guided by the International Society for Technology in Education's (ISTE) guidelines (*ISTE Standards*, 2024). This definition of CT is guided by and scrutinised through existing research on what is developmentally appropriate for young children, relying on existing education research on what can be scaffolded in early childhood. This section discusses the early development of CT foundational skills and the need for activities to thoughtfully include digital technology, existing digital CT tools for children under 5 years and corresponding studies (see Table 1 for a summary). Furthermore, existing studies are unpacked to inform our design-oriented research approach (Fallman, 2003) with respect to how children explore and develop their understanding of CT processes.

2.1 Early childhood and development of CT

The ability to formally teach foundational concepts of CT to very young children has undergone considerable scrutiny as educators review the value of learning CT skills. Researchers have argued that very young children may not yet have the cognitive ability to perform necessary tasks to show understanding of rudimentary CT principles such as logic (e.g., procedural step-by-step problem-solving, e.g. to tell a friend to go to the shops) and achieve perspective-taking (e.g. converting code to

Table 1 Overview of current knowledge regarding research conducted with digital toys and the learning CT skills

Supportive Interactions	CT Tool	18–36 Months CT Research	3–4 years CT Research	4–5 years CT Research
Fine motor skills (Bakala et al., 2021)	N/A	Untested, should see development	Untested, should see development	Developing
Social interaction and play (Critten et al., 2022; Odgaard, 2022; Vygotsky, 1980)	Bee-Bots (Bakala et al., 2022; Critten et al., 2022; Odgaard, 2022), Alert (Burleson et al., 2018)	Untested, should incorporate individual play with adults and peers	Individual play with collaborative play developing. (Critten et al., 2022)	Collaboration developing (Critten et al., 2022; Odgaard, 2022)
Physical involvement (Burleson et al., 2018)	Alert (Burleson et al., 2018)	Untested, should be developing	Unknown, should be developed	Developed
Communication of problem (Su & Yang, 2023)	Bee-Bot (Critten et al., 2022)	Reported only with unplugged, everyday familiar tasks. Not with Bee-Bots (Critten et al., 2022)	Reported only with unplugged, everyday familiar tasks. Not with Bee-Bots (Critten et al., 2022)	Developing critical inquiry methods (asking questions) (Critten et al., 2022)
Readiness for computational thinking	CT Tool	18–36 Months	3–4 years	4–5 years
Procedural thinking (Critten et al., 2022; Grover & Pea, 2013; Saxena et al., 2020)		Reported only with familiar tasks with pictures (unplugged (Critten et al., 2022))	Familiar Tasks with pictures and sequencing stories (unplugged (Critten et al., 2022)) Not yet visualizing multiple steps (plugged Bee-Bot Critten et al., 2022; Saxena et al., 2020))	Developing three step instructions for robots (Bers, 2010; Critten et al., 2022)
Knowledge of CT Symbols (Critten et al., 2022; Grover & Pea, 2013; Saxena et al., 2020; Wyeth & Wyeth, 2001)	Bee-Bot, Electronic blocks	No evidence. Should see developing knowledge of Symbols	No evidence. Should see developing knowledge of Symbols	Limited evidence. Should see developing knowledge of Symbols (Critten et al., 2022)
Debugging (Grover & Pea, 2013; Wyeth & Wyeth, 2001)	Bee-Bot	Unknown	Unknown	Developing

Table 1 (continued)

Supportive Interactions	CT Tool	18–36 Months CT Research	3–4 years CT Research	4–5 years CT Research
Conditional Logic (Grover & Pea, 2013; Wyeth & Wyeth, 2001)	Electronic Blocks	Unknown	Unknown	Developing in understanding of 'toggle' switches and 'Not' blocks (Wyeth & Wyeth, 2001)
Defining Patterns (abstraction and algorithms) (Saxena et al., 2020)	Unplugged & Bee-Bots	Unknown	Recognition of Patterns (unplugged (Saxena et al., 2020))	Developing (with Bee-Bots Bers et al., 2014; Saxena et al., 2020))
Direction perspectives (Bakala et al., 2022; Saxena et al., 2020)	Bee-Bots, Kibo, Botley, Robotito, Bluebot	Not yet	Not yet	Developing (plugged with Bee-Bots Critten et al., 2022; Saxena et al., 2020))

program a robot) (Piaget, 1973; Simões Gomes et al., 2018). However, research has shown that undertaking simple CT activities, such as sequential programming, has shown positive gains in cognitive abilities such as spatial awareness and executive functioning (Bakala et al., 2021; Messer et al., 2018; Papert, 2020).

Play and social play are developmentally appropriate learning methods in early childhood education. In informal environments, play is a broad term encompassing free and adult-scaffolded play and is predominantly child-led (Hewes, 2006). In formal environments, play becomes more structured towards obtaining adult objectives that form the basis of learning activities. Early childhood educators foster young children's ability to engage in situated and meaningful free play, an inherent part of learning creative problem-solving (ACECQA, 2022; Knoop, 2002; Vygotsky, 1980). As technology is further embedded into daily activities, children's play has also begun incorporating physical and symbolic representations of different forms of technology (Bird & Edwards, 2015; Chu et al., 2024; Vygotsky, 1980, p. 101). Although researchers discuss 'play' as a fundamental part of CT activities, children's interactions with digital technologies in free play are often neglected, prioritising research into more formal activities (Bers et al., 2014; Quinn et al., 2023). Consequently, a lack of understanding persists regarding what CT knowledge young children can gain through digital tools. Although research is growing in early childhood education, there is still a lack of knowledge regarding the types of CT activities that are beneficial and support young children's exploration of technology, leading to further understanding of how technology works and what can be done with it, which are core components of digital literacy and CT (Erstad & Gillen, 2019; Wing, 2006).

Current research has discussed what activities should be possible considering known developmental milestones in childhood. An exploratory study by Saxena et al. (2020) discussed CT competencies in line with the guiding principles of Piaget's cognitive development. (However, some criticism has been raised regarding the exact age range in which children show developmental leaps (Babakr et al., 2019)). Saxena et al. (2020) advance that the four stages of development (sensorimotor, preoperational, concrete operational, and formal operational) can be used to understand what types of CT activities are appropriate to offer young children depending on their stage of development. Their discussion outlines that young children (2–7 years) have the capacity for symbolic thought, evidenced by their use of language for meaning-making, engagement in pretend play, and solving problems, which are oftentimes not evidenced in their use of existing CT tools. CT tools often rely on symbolic directional language to 'program' their movements, as well as a shifting perspective from themselves to the robot to solve problems. Piaget (1973) also theorised that logical thought and the ability to understand different perspectives are still in the early stages of development for young children in this age group. Similar findings were reported in more recent studies where young children showed difficulty understanding the perspective of a turning robot with how they (the children) turn (Clarke-Midura et al., 2021; Critten et al., 2022; Silvis et al., 2020). Other studies also suggest that young children can implement CT practices, including sequences of activities, i.e. instructions from one point to the next, and recognise instruction patterns with digital CT tools, which form foundational knowledge in understanding algorithms. However, when using digital CT tools they have difficulty moving towards articulating multiple-step processes (algorithm design). A study by Critten et al. (2022) explored how very young children (aged 2–4) can understand aspects of CT with and without adult-led play using a digital CT tool (Bee-Bot, 2024) and non-digital materials. Results showed that young children can independently learn the fundamentals of CT when non-digital materials are employed and when activities are suited to their developmental level. However, they could still produce content with other digital CT tools only when scaffolded with 1 to 1 adult-led play (Bofferding et al., 2022; Critten et al., 2022). Similarly, Newhouse et al. (2017) looked at how preschool children played with Bee-Bots, a traditional CT digital tool and Sphero. They used Bird and Edwards's digital toy framework (Bird & Edwards, 2015) to ascertain the types of learning evidenced in young children's play (Explorative and Symbolic Play). They found that although children explored the digital toys, they did not show a developed understanding of directions and multiple-step processes unless scaffolded by an adult (Critten et al., 2022; Saxena et al., 2020). These findings underline adults' importance in fostering developmentally appropriate CT activities with digital materials. Still, more importantly, they highlight that the current digital tool resources used in informal environments may not yet be developmentally appropriate for child-led activities.

Although researchers acknowledge the need for further longitudinal studies (Sodian et al., 2020), these studies reveal that young children can learn foundational CT knowledge. However, there is a gap between what can be developmentally expected from young children's free-play activities and the types of activities current digital tools support. Research into what CT activities young children are developmentally ready for provides an essential first step in ascertaining the possibilities of designing tools that facilitate children's CT skill development. These possibilities include developing tools that can be incorporated into child-led free play that is meaningful to the child, solving multiple-step problems, and using symbolic language that doesn't require directional knowledge, with a reduction in perspective shift orientation.

2.2 Unplugged vs plugged activities

In the early years of education (informal or formal), non-digital, i.e. unplugged activities, have gained notable traction in supporting children's fundamental skills in CT. As this paper focuses on digital tools, it is important to discuss why there is a need for plugged tools in the younger years when seemingly easily obtainable activities through unplugged activities exist (Bakala et al., 2023; Grover & Pea, 2013; Yu & Roque, 2019).

The use of unplugged activities provides benefits for learning computational thinking for young children, as the activities and the materials are items that children are readily familiar with, such as drawing, cutting, and pasting. Familiar activities allow young children to take ownership in learning foundational content rather than learning new icons and symbolic language (Critten et al., 2022; Silvis et al., 2020), for example, using concrete analogies that are easier to make sense of, such as procedures for getting dressed or giving directions (Brackmann et al., 2017; Saxena et al., 2020), in contrast to the abstract and complex knowledge needed to program a robot (i.e. perspective taking, meaning making of symbols, dislocated tasks). Unplugged activities have often been heralded as being of benefit to younger children as activities incorporate the use of space and body movements that promote embodied learning (Hu et al., 2023; Montuori et al., 2023). Furthermore, educators and parents often report being overwhelmed by needing to learn new content and skills. In this sense, therefore, unplugged activities can offer an alternative method without the sacrifice of critical developmental gains in learning CT (Akiba, 2022; Brackmann et al., 2017; Lee et al., 2023).

One of the major drawbacks of using unplugged activities stems from discussions that suggest that unplugged activities may not be transposed easily into digital literacy, which is crucial for the continual development of CT skills, especially in later years (Grover & Pea, 2013). Research indicates that unplugged activities may promote different learning outcomes to plugged activities (Grover & Pea, 2013; Lin et al., 2023), suggesting that young children need both activities to ensure the holistic development of foundational digital literacy and CT skills, including incorporating technology into social spaces, which provides opportunities for meaningful interactions (Erstad & Gillen, 2019). These findings have meant researchers in pedagogical environments focus on integrating multiple paths to ease this transition for children and afford them the benefits of multiple activities (Akiba, 2022; Erstad & Gillen, 2019; Montuori et al., 2023).

2.3 Computational thinking and digital tools: what are the problems?

As discussed in Sect. 2.1, there are some concerns regarding how existing digital tools support the learning of CT. Researchers (Bati, 2022; Yu & Roque, 2019) have identified three main types of Digital CT tools: vehicle-based, block-based, and open-ended digital tools. Findings from these studies show that vehicle-based Bee-Bots are the most predominant tool studied with children under 5 years. The following section of this paper discusses how these tools have been used to support CT learning and what researchers have learnt through investigating these tools. An overview is provided in Table 1, detailing what researchers of CT have discussed as fundamental knowledge that has yet to be realised in the design and use of CT tools for children under 5 years.

2.3.1 Vehicle-based CT tools

There are many vehicle-based CT tools. However, Bee-Bots are possibly the most well-known as they are simple to learn and adaptable to multiple activities (Bakala et al., 2023; Yu & Roque, 2019). Bee-Bot tools are screen-less CT digital tangible tools that encourage young children to learn essential CT situated in a stepwise process (Bers, 2010; Bowen et al., 2022). The tasks often evolve around picking an endpoint and using maps, grids, or random objects on the floor to navigate a Bee-Bot, providing opportunities for children to learn how to plan a procedure

(Clarke-Midura et al., 2021; Critten et al., 2022), iterate on the correct usage of buttons and paths (Bakala et al., 2021), and debug their ‘program’ or the technology of the Bee-Bot (Misirli & Komis, 2023). However, research also suggests that Bee-Bots and other vehicle/robot-type tools are problematic in four main ways, including in play-based environments, in their use of symbols to indicate movement, in their need for children’s ability to shift perspective, and in their inability to promote social learning.

Play-based environments Young children engage in learning practices, which are formed in play-based activities that are spontaneous and child-led (Hewes, 2006; Kotsopoulos et al., 2022; Montessori, 2004). However, questions have been raised over whether Bee-Bots can support CT where scaffolding is used in response to children’s problem-solving abilities (Bers et al., 2019; Bofferding et al., 2022; Kotsopoulos et al., 2022; Lee et al., 2023; Yu et al., 2020). Odgaard (2022) reported on observations of children prioritising social situations or goal attainment over programming the robot, suggesting that educators’ objectives of developing skills in CT are often thwarted. In addition, Odgaard (2022) suggests that several environmental factors need to be considered before educators use Bee-Bots to support children in gaining CT skills. First, determine how children should ‘code’ rather than relying on buttons, which promotes memory sequence over coding and debugging. Specifically, Odgaard noted that children not supervised by an adult will prioritise getting where they want the Bee-Bot to go by picking up and moving the Bee-Bot rather than debugging their code. Second, Odgaard posits that it is important to consider the social environment and activities that enable children to engage in authentic, age-appropriate collaboration.

Symbols and movements in the world Silvis et al. (2020) explored how children in Kindergarten understood CT by using Bee-Bots. They reported that children’s embodied knowledge of direction created tension when children began using symbolic notations to predict where the Bee-Bot would move. Specifically, the Bee-Bot’s turn on the spot, different to how children understood ‘turning’ from the embodied practice of running or riding around a corner, which is conceptually distinct. When interacting with the symbol on the Bee-Bot, children interpret this to mean the latter (being a gently curved arrow), creating a problem for children who could not reconcile the curve of the symbol with the movement of the Bee-Bot. Further research is warranted to understand children’s embodied knowledge and how they interpret symbol use on digital CT tools.

The current study aims to add to the existing body of literature by understanding what young children’s embodied actions can tell us about how they start to understand CT and how embodied knowledge of the world takes precedence over new information. Furthermore, this research aims to deepen our understanding of children’s use of symbolic representations in contextually relevant situations to aid rather than obfuscate knowledge building (Burleson et al., 2018; Gaver, 1991; Manches & O’Malley, 2012). Therefore, we need to carefully consider the following aspects in the development of CT tools, i.e. to ensure symbols, interactions, and affordances do not introduce tensions in children’s developing understandings.

Shift in perspectives Critten et al., (2022), implemented three main high-level adult-led scaffolded activities – Doll care, Building Maps, and Bee-Bots, with children aged 2 to 4 years. Results show younger children (approx. 2 years) can collaboratively choose appropriate materials for a task such as 'baby doll bathing' and communicate a step-by-step procedure using picture codes. However, children required increasing levels of 1 to 1 support as tasks shifted to using Bee-Bots and became increasingly more: 1) symbolically directional oriented, i.e. left, right, 3 steps; 2) sequentially complex, i.e. mapping an algorithm of three or more steps; and 3) complex as they moved from 2D representations to 3D representations, i.e. using a 2D map to walk around a garden. Critten and colleagues suggest that existing CT tools such as Bee-Bots, which require symbolic, multiple steps, and a shift in perspective, may be developmentally challenging for children between the ages of 2–4 and often are instead appropriated as a push-button tool. In addition to the findings, other researchers have also discussed children's ability to change perspective easily may be limited during CT activities (Bakala et al., 2022; Saxena et al., 2020).

Young children's ability to socially learn Very young children often learn from watching and learning from each other or through collaboration (Meltzoff, 1999; Vygotsky, 1980). Researchers investigating how current digital tangibles engage children in learning practices suggest tangibles must include an ability to support multiple users to determine inputs and outputs and problem-solve around them (Bakala et al., 2022; Burleson et al., 2018; Critten et al., 2022; Odgaard, 2022). In addition, there have been several researchers who have explored how collaborative learning with vehicle robots could be designed, including the use of enlarged coding blocks such as floor tiles to promote multiple viewpoints and body movements for 'just in time' coding practices (Burleson et al., 2018), using feedback that supports group work rather than individual work (Bakala et al., 2022; Matthews & Matthews, 2021), supporting multiple positional perspectives, and fostering children's use of curiosity to support initial engagement that encourages other children to try (Bakala et al., 2022).

2.4 Robotics and block based CT tools

To support the coding of robotic tools, researchers have incorporated tangible programming blocks with robotic vehicles, such as Kibo (Bers, 2018), Cubetto (Caguana Anzoátegui et al., 2017) and Electronic Blocks (Wyeth & Wyeth, 2001). These CT tools partially address the problem of ensuring children learn how to structure linear code to move a robot rather than being able to move the robot manually without the use of code, which is prevalent with Bee-Bots (Bers, 2018). These types of tools separate the 'coding' of the robot from the robot by using tangible blocks and puzzle pieces containing coding symbols and readable data to control a decoupled robot, i.e., as code is built, it can be tested by pushing the code to a vehicle robot, or by stacking coded blocks on top of each other to see how the robots perform tasks. The separation of the robot and the code provides young children avenues for iterating and building knowledge of coding without interfering with the resultant behaviour of the robot. These types of CT tools often have sensors and have also incorporated conditional statements, building knowledge in coding skills and understanding of technology, which is fundamental in developing skills in CT (Bers, 2018; Wyeth & Wyeth, 2001). The disadvantages with these types of tools are 1) symbols are used on the blocks and need to be interpreted by the children (Wyeth & Wyeth, 2001) (see above section for literature discussion); and 2) the decoupling of the robot from the programming blocks increases cognitive load, which is discussed below.

Decoupling adds to cognitive load In several interviews conducted with preschool teachers regarding the usage of Digital CT tools in a play environment (Bakala et al., 2023), educators highlighted the problems of using blocks or cards that had to be manually uploaded to a device and how decoupling the code from the actions of the device increased children's inability to iterate and debug (Bakala et al., 2023). Educators in this study described young children's movements as unintentional – often uploading the code from the block nearest to them rather than the one in the sequence. In addition, these educators reported that when the device was run, it wasn't clear which part of the code was being 'played' out. As such, the reliance was placed on the educators being able to upload the code and describe how the code was being enacted in the robot.

2.4.1 Open-ended CT tools

The use of open-ended CT tools is still in its infancy, and only a small collection of tools has been developed in response to finding alternatives to vehicle-based CT tools. Furthermore, very few studies have been conducted on using open-ended CT tools in early-year environments. An example of an open-ended CT tool is Code-attach (Yu et al., 2020), developed in response to a lack of open-ended, creative, tangible digital CT tools for younger children. It is a novel tangible tool aimed at children 7–8 years old. Code-attach aimed to increase opportunities to engage children in playing physically and creatively with code, in contrast to more traditional sedentary activities of coding. The tool consisted of tangible code blocks that could be used to program a tool that Velcro fastened to objects such as clothes or walls. The open-endedness of the tool created opportunities for children to design activities, including iterating on versions of hopscotch and hacky sack (Yu et al., 2020). The reported benefits of such a tool include that children can take ownership of the CT experience through play and that rules can be created and implemented by enabling the development of iteration, debugging and algorithmic thinking situated in an open-ended computational thinking process.

2.5 Summary

In summary, there is a growing body of research in tangible, non-screen-based CT tools for young children. However, a lack of understanding exists regarding how or if young children (aged 18 – 36 months) can begin to show fundamental understandings of CT through playful interactions with tools, particularly given the narrow selection of tools (Clarke-Midura et al., 2019; Yu & Roque, 2019). Therefore, this creates limited opportunities for understanding the breadth of possibilities that can support the development of CT skills.

Research suggests that for young children to start to use tools for learning CT fundamental skills then, digital CT tools need to 1) be supportive of child-led narrative play, 2) include symbols and movements that connect rather than create tension with children's embodied understanding of the world and that the tool supports contextually rich opportunities for children to program 3) limit the amount of decoupling needed to perform a task 4) be examined given other CT tool-related forms and interactions (rather than supporting only robotic vehicle-based tools) that are social, creative and open-ended.

This literature review provides an impetus to discern how young children and parents incorporate computational thinking in play with digital tools and what design features facilitate developmentally appropriate CT experiences.

3 Methodology

This paper presents a design-led research study to investigate alternatives (in both form and function) for CT tangible tools for young learners (See Fig. 1). Design-led investigations can take many forms (Fallman, 2003; Frens, 2007; Gaver, 2012; Koskinen et al., 2013) but share particular distinctions with respect to the logic of their inquiry. Design is not a deductive process (Kolko, 2010). While responsible design processes must be informed by careful research of people, contexts of use, environmental and institutional requirements, engineering possibilities, prior art, etc., an exhaustive appreciation of these concerns is insufficient to *determine* the products, systems, or services to design. A characteristic of design is that there are always many additional possibilities, even after satisfactory design proposals have been advanced, and therefore, "design cannot be data-driven" (Sharrock & Anderson, 1994). For this reason, design is never simply an optimisation problem nor reducible to requirements engineering (Schön, 1992).

Furthermore, designers cannot fully know the consequences of their designs before those ideas are manifested in some form. This is one of the reasons that prototyping is an essential aspect of the major 'models' of design processes, and as such, building and deploying early versions of designs are essential components of establishing an understanding of the problem spaces (or opportunity spaces) for which they are designed. Prototypes play essential roles in research as they integrate design as part of the methods of inquiry (Wensveen & Matthews, 2014). The design proposals that researchers prototype in design-led inquiries are not 'just' ideas, nor should they be understood as hypotheses or predictions about their effects on the world. Instead, they are a targeted means of inquiry through which understandings about both design (how and what to make) and the human worlds we are designing for are developed (c.f. Schon, 1983). Design 'probes' (B. Gaver et al., 1999;

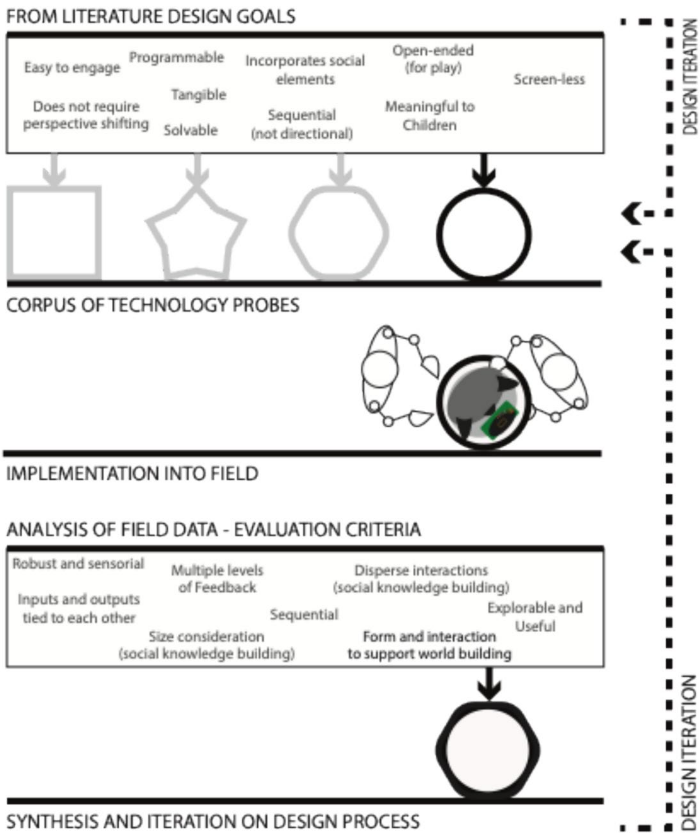


Fig. 1 Overall design-led research process, indicating the iterations that occur through implementing probes into the field

Hemmings et al., 2002; Hutchinson et al., 2003; Mattelmäki, 2005) are crafted explicitly with such an understanding in mind—as tools of inquiry in open design spaces.

As part of a larger project, this study was conducted through a design-led research process with children (Ejsing-Duun & Skovbjerg, 2019; Sanders & Stappers, 2008). Specifically, the study deployed a novel technology probe that sits in contrast to existing traditional CT tools (designed for older children). The designed technology probe included distributed interactions between three plush toys and outputs haptic and visual feedback, creating a novel experience. The novel interactions, coupled with tools very young children are likely to be familiar with, are designed to examine the effectiveness of engagement through play. Furthermore, such designs also aim to determine if a simple programming mechanism of 'proximity reactions' can be an effective way to provide foundational knowledge of CT beyond that of pushing of a button in very young children.

The observational studies of children's interactions with our technology probe 'Embeddables' are described below. The longer-term aim of the study is to see possibilities for future development of CT tools targeted at building a range of CT experiences as part of either free or scaffolded play. The participants, activities undertaken, and data analysis methods are described below.

3.1 Technology probes

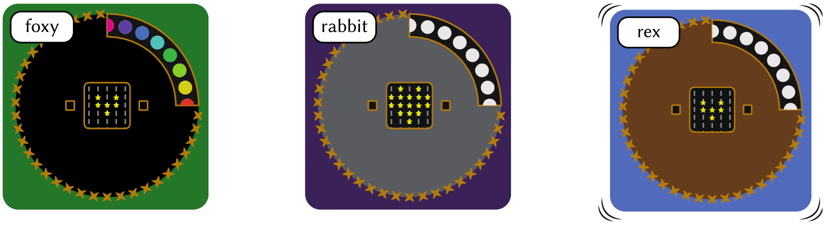
Technology probes are used in design-led research to elicit feedback from field studies (Hutchinson et al., 2003). Traditionally, technology probes are simple and adaptable technologies that allow researchers to field test before developing more costly prototypes. They can be both off-the-shelf and/or bespoke technologies, depending on the requirements of the intervention (Matthews et al., 2024). In this way, technology probes provide avenues to understand constraints and user needs beyond those of deploying existing technologies, providing a strong warrant for the current study. Technology probes complement and are often used in conjunction with traditional ethnographic methods in understanding cultural settings, such as interviews and observations (Gaver et al., 1999; Matthews et al., 2024).

3.2 Design of embeddables

The technology probe 'Embeddables' was designed to sit in contrast to existing vehicle CT tools, allowing for the following five features: 1) open-directional and multi-modal interactions, 2) conditional programming, 3) limited symbol use, 4) a distributed system for social learning, and 5) promotion of playful embodied learning. Although there are many opportunities presented in literature, this study has been designed to further explore these features in tools for very young children.

Open-directional and multi-modal interactions Technology is intentionally embedded into commercially available soft plush toys to provide opportunities for

Fig. 2 The three Embeddables respond through broadcasting radio signals that trigger actions in close proximity to each other. Embeddable-rex (left) vibrates and displays a light emitting diode (LED) array. Embeddable-foxy displays led animations and a LED array. Embeddable-rabbit displays LED array (hearts)

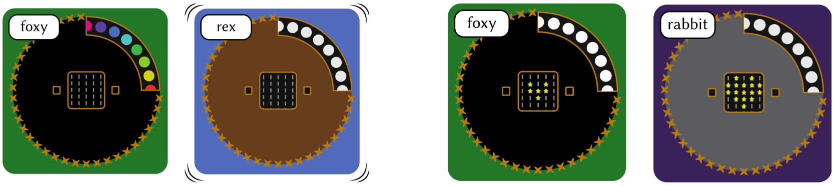


Embeddable ‘foxy’ responds to proximity of ‘rex’ through output of strip LED light, responds to ‘rabbit’ through LED array.

‘rabbit’ responds to proximity of ‘foxy’ & ‘rex’ through output of LED array.

‘rex’ responds to proximity of ‘foxy’ through vibration and ‘rabbit’ through LED array.

Fig. 3 Embeddables (foxy, rabbit and rex) are a technology probe that can be embedded into soft toys to determine if children respond to them in a way that highlights their usefulness as a CT tool



a) Embeddables-foxy and rex in close proximity: foxie’s LED lights turn on, rex’s vibration motor turns on.

b) Embeddables-foxy and -rabbit in proximity: -foxie’s LED array light turns on; rabbit’s LED array turns on in sync with foxy.

Fig. 4 Embeddables change behavior as they are brought in proximity to each other

cuddling, throwing, and multi-directional movement (Fig. 2). These interactions are in contrast to interactions typical of vehicular toys, such as pressing, pulling, and sliding. In considering the design of these digital characters, we were also interested in whether children would talk to the toys or involve them in other multi-modal play. The range of interactions (not just *of* the successful activation of the technology in Embeddables, but of children’s attempts to engage *with* them) aid in understanding how alternative modes can help children explore CT processes.

Conditional programming An alternative means of enabling children to encounter an if–then-else coding concept was implemented in the design (Wyeth & Wyeth, 2001; Yu & Roque, 2019). Proximity reactions in the Embeddables were designed to be triggered by the children’s likely interactions with the tool’s affordances (e.g. throwing and open-directional movement). Specifically, the aim was to explore if or how such coded behaviours of the Embeddables might be understood (and manipulated) by young children. A set of simple ‘if–then-else’ proximity reactions were implemented for children to discover and select depending on the output they might seek to trigger (Fig. 3 and 4). Currently, tangible coding is often designed with symbol blocks that are positioned one after another based on the findings from studies that report that young children have found it difficult to understand what the symbols represent (Gaver, 1991; Manches & O’Malley, 2012; Silva et al., 2022; Silvis et al., 2020). We also considered alternative approaches to exposing children to coding concepts in play, aiming to identify how other actions, interactions, and relations embedded in (and between) tools may create productive avenues for children's exposure to CT.

Symbol use Symbols are limited to outputs rather than as guides to interactions (Critten et al., 2022; Silvis et al., 2020). As such, this study aimed to determine if very young children became aware of these symbols rather than to determine if they understood their meaning. Such an approach also ensures that the symbols used are not misrepresented and that they provide a simple, meaningful interface for initial interactions with the probe.

Distributed system for social learning The digital system is distributed between different plush toys, and therefore encourages multiple users (Bakala et al., 2023; Burleson et al., 2018). This functionality was included in the design of the Embeddables used in this study to determine if young children and children's adults would or could interact in a social manner with the devices (Fig. 4).

Playful embodied learning The Embeddables were designed to be set into traditional plush toys, to understand the types of playful activities children might want to enact, to see how the digital technology may support or hinder that activity, and how their play compares to traditional play with non-digital plush toys. Observations of what children do with digital tools provide insights for the design of future CT tools.

The distributed nature of the interactions and the haptic and visual feedback provided by the outputs created a novel experience that is coupled with familiar tools and an environment conducive for young children to play in. The familiarity of the toy provides a guide to determine how the tool might be interacted with (like the vehicle robots that move along the ground), however traditional usage is offset with novel interaction that prompts a basic level of problem solving (i.e. 'how do these work together?'). Therefore, the probes provide an avenue through which to investigate our research questions: how young children and parents incorporate computational thinking in play with novel digital tools (Kotsopoulos et al., 2022) and extract the types of design features from the novel probe that facilitated different CT experiences (i.e. Symbolic reasoning, procedural problem solving).

3.2.1 Embeddables technical description

The technology probe consists of an outer fabric pocket that houses microcontrollers, sensors, outputs, and batteries. The pockets are either sewn in or Velcro-attached onto everyday objects (in this case plush toys). The Embeddables have been coded so that the outputs change depending on how close each of the individual radio broadcasting signals were, creating a distributed system. Independent push buttons (that were able to be used by the children) were incorporated and linked to a separate light emitting diode (LED) array as an added interactional security measure (i.e. check for battery level and connection). Commercially available plush animals were chosen to house the Embeddables as a contrast to traditional vehicle

CT robot tools, and to determine how other interactions might influence children's embodied responses. Specifically, we speculated that characters (Embeddable-rex, Embeddable-rabbit, Embeddable-foxy) might encourage more relational play (orienting to the Embeddables as having relationships between each other or as having distinct personalities) that could promote social play. The 'Embeddable' characters were not connected to popular culture characters or 'families' of characters (i.e., all rabbits or farm animals), and therefore, there were no predetermined or expected ways to incorporate them into play. Rather, the toys that children could choose from included unrelated brightly coloured toys that resembled a dinosaur, a rabbit, and a fox.

3.3 Environments of observational studies

The technology probe was initially deployed in an Australian Children's Museum located on the main campus of a major (regional) university. The Children's Museum is open seven days a week for families. The play space includes several experiences, such as a marketplace, a large ship, outdoor spaces, and a campfire. Experiences are designed with researcher input to provide evidence-based activities encouraging curiosity, creativity, and other positive, supportive learning interactions. This research was conducted during a focused day across the museum on digital play; researchers and practitioners working together throughout the entire space planned and facilitated digital encounters. These activities included Bee-Bots, drawing with robots, slow-motion filming of experiments, multimodal storytelling, and the use of Makey Makey kits (amongst others). Embeddables were placed in several museum locations, including in a quiet play 'campfire' corner, in the ship, and in a play tent within the Museum. An iPad was used to film general interactions, and a roving iPhone was used to capture more detailed interactions (see Sect. 3.3 for protocol). To ensure the team could determine if children and their adults were motivated to play and use the technology probes, educators or researchers did not explicitly scaffold interactions with the Embeddables. A researcher, however, was available to answer questions about the technologies and how they worked.

3.4 Compliance with ethical standards

Children and their adults (parents/guardians/carers) were invited to the 'Festival of Digital Play', where they could engage with the Embeddables while at the Children's Museum. Children's adults were invited (without obligation) to sign a consent form to participate in the study on behalf of themselves and their children upon entering the Museum (HR2022/107). Before video data was captured, additional verbal consent was sought from the children's adults and, where possible, from the children themselves. Over three hours, 16 children (aged approximately 18 to 36 months) and their caregivers interacted with Embeddables. Time spent with the Embeddables ranged from 2 to 8 min, with shorter times due to no adult scaffolding and longer times with adult scaffolding.

3.5 Analysis of video data

The research team was comprised of researchers from the fields of interaction design, computer science, and early childhood education. Video analysis methods have been adapted from Jordan and Henderson (1995) and Heath et al. (2010). Video data was transcribed and initially divided into each child and caregiver's engagement with the technology probes (16 video sections). The first author conducted an initial video selection, focusing on extended interactive sessions and repeated behaviour across videos (for example, when four children were seen throwing the Embeddables on top of each other, one of the videos was included in the selection). The initial video selections were then shared and discussed with the research team via video conferencing software over several sessions. Discussions centred around 1) how young children and their adults engaged the technology probe, 2) how adults naturally described the interactions and how these could be leveraged to explain CT foundational principles for both children and their adults and 3) the possibilities for further development in alternative digital tool designs. A detailed transcription was produced with corresponding interactions and analysed, specifically looking at initial interactions, the scaffolding of adults, sequences of interactions, and types of problem-solving with the technology. This paper presents some of the more pertinent cases to ensure the data is situated in context. From the analysis, team members focused on the attributes of the probes that enabled or facilitated interactions, responding to our research question (see Sect. 1). These are presented in the discussion.

4 Results

The team introduced CT technologies in a Children's Museum, with adults and their children aged approximately 18 – 36 months. The study observed how these young children interacted with the technology probes 'Embeddables' to determine if we could notice CT experiences developing in play with novel digital tools (Kotsopoulos et al., 2022) and to extract the types of design features that facilitated different CT experiences. The Embeddables were positioned in play areas for the children to interact with without any specific initial introduction or intervention. Any subsequent interventions or scaffolding of their play by the researchers was opportunistic, either building on children's existing interactions or occasioned by instances when children were displaying difficulties in understanding how to operate the technology. Below, we present three cases that are typical of the interactions witnessed throughout the field data and our key observations of the children's (and caregiver's) interactions with Embeddables. These are: 1) unexpected moments prompt exploration; 2) Embeddables prompt proximity problem solving; 3) Embeddables manifest social play.

Our key observations are that CT digital tools create opportunities to explore the digital world, that proximity reactions support procedural thinking, that different vocabularies of 'directional knowledge' have implications for instructions, that feedback in tools needs to be considered not only for the child but also for a third party; that intermittent functionality in tools creates issues for educators' explanations; that CT language use can be supported through basic tool mechanics linked to simple explanations; that tools that contain a distributed interactive system across different tools can support social play.

4.1 Case 1: unexpected moments prompt exploration.

The Embeddables were often thrown, shaken, or rolled on top of, which created unexpected moments in the play. As the plush animals were thrown together by the children, their interactions would change, causing the children to pause to watch the Embeddables. Children would often move towards the Embeddables and pause mid-activity to either watch the LEDs or feel the vibration in the motor. For example, Fig. 5 shows a toddler picking up Embeddable-foxy, and then shows how the child sees the Embeddable-rex flashing. As a result of this flashing, the child throws the Embeddable-fox away and crawls over to the Embeddable-rex. The child pulls the Embeddable-rex by the arm towards them to gain a closer look but pauses as they feel the vibrations (See Fig. 5b). The child sits up and uses their left hand, not letting go of the arm with the right, touches the Embeddable-rex's mouth, watching the LED screen light up (Fig. 5d).

4.1.1 Purposeful digital tools create opportunities to explore the digital world as part of the real world

In Case 1, although the child is young and is yet to understand how technology works, we can see from this case that tools with purposeful digital interactions can increase awareness of the digital world and prompt curiosity and exploration,

a) Charlie sees the Embeddable-rex and crawls over [21: 00'04]

b) Charlie grabs the arm to pull the Embeddable-rex over to them [21: 00'07]

c) Charlie sits up to explore the Embeddable. [21: 00'09]

d) Charlie holds on to the arm as it vibrates, using the other hand to feel its face [21: 00'27]

Fig. 5 A toddler crawls over to explore the Embeddables the beginning foundations of CT. The interaction starts with the child crawling and picking up the Embeddable-foxy, demonstrating that it is through this chance encounter that the -rex starts to flash its LED, encouraging the child to come over and further explore. The Embeddable-foxy is discarded, and the Embeddable-rex now becomes the object of attention. This simple interaction, an interaction that invited and prompted curiosity and exploration, provides impetus to engage in further inquiry into the possibilities that might exist to encourage digital exploration for very young children – explorations that may turn into more purposeful interactions as children's CT continues to develop. These key observations suggest that further investigation could explore what would happen once the -rex was held and prompt a noise to be emitted by a nearby tool, such as the Embeddable-rabbit. Such an investigation could then determine whether this type of functionality may then lead to further explorations by of the child, and/or whether such a function could prompt and encourage procedural play.

4.2 Case 2: embeddables prompt proximity problem solving

Key observations also showed that young children were often observed watching and exploring the technologies, moving them from place to place. When one embeddable was moved away from the others, the outputs of the technology stopped working, causing the child to stop. Parents then were able to step in and discuss with their child what was happening, that is that the other embeddable 'friend' needed to be close for the embeddable to work again. The interaction with the child and the Embeddables created embodied procedural moments where one 'friend' was systematically placed with another to determine what worked at what time. An example of this type of procedural play can be seen in the following excerpt where a mother was holding a baby while exploring the

a) Sas walks over and picks up the Embeddable-rex. They notice that the tool flashes and vibrates [33'54]

b) Sas walks with the Embeddable-rex, until they realise that it no longer vibrates. [34'23]

c) Sas finds Embeddable-foxy after their adult asks, 'where is fox?' [34'45]

d) Sas turns Embeddable-rex around holding it next to Embeddable-foxy [34'57]

e) After successfully finding all the Embeddables, Sas places them one by one in the tent [37'00]

Fig. 6 A young child plays with the Embeddables in a 'campfire' environment at the museum

Embeddables with their child, aged 2 years. We unpack this case in the following sections.

The child runs up to the fireplace opening pots and pans, pretending to make a meal. *"It's a fire, a fire, a fire!"* the child excitedly exclaims, the mother walks over (carrying a baby) to the fireplace and asks, *"What are you making?"*. She notices the plush teddies and states *"And look at all the friends, look at the dinosaur!"*, the child responds *"Yeah!"* The child moves to pick up the Embeddable-rex, pauses and then turns the Embeddable-rex facing him [Fig. 6a], first watching the symbols flash on and then moves his hand to feel the tools face *"Wow!"* says the mother. The child then walks, past their mother, with the Embeddable-rex [Fig. 6b], and then stops, and puts the Embeddable down watching it closely (The embeddable stops flashing). The mother turns from watching what the child is doing, to the research and asks, *"do they do anything?"*, the research walks over and gives a brief explanation *"so then they are friends, so when they are joined together, they will do something"*. *"Rah"* states the child, the mother imitates *"Rah"*. The child then points animatedly at Embeddable-rex prompting the mother to say *"You want the dinosaur? Do you want to put the, where's the fox?"* The child turns to the other Embeddables, *"Where's the fox?"* says the mother again, "There" says the child pointing towards embeddable-fox. *"There"* confirms the mother *"do you want to put the dinosaur next to the fox, because they are friends!"* The child walks over and picks up Embeddable-fox [Fig. 6c] and then walks the fox over to Embeddable-rex. *"Do you want to put them next to each other?"* asks the mother. After placing the fox next to the dinosaur, the child becomes excited *"Owr to dis dis one", "okay"* confirms the mother *"There we go"*. *"Der's de rah!"* states the child [Fig. 6d], *"Yes the rah! put the dinosaur next to him"* says the mother, the child continues *"De er what ni"*. The mother states *"Is this soft?"* the child answers *"Di" "Yeah, it's very soft"* confirms the mother. The child then takes the embeddable-fox back to the fireplace *"And what about the rabbit, do you see a rabbit?"* asks the mother, the child picks up the embeddable-rabbit. "Yeah, there's *the rabbit, shall we bring the rabbit next to the dinosaur? Oh yeah!"* The child asks, *"De you com ove den?", "Okay"* says the mother. *"Rah"* says the child again and throws the Embeddable-rex in the tent, *"Ahh you put it in the tent! Are they all going to go in the tent?"* Asks the mother [Fig. 6e] "Yeah!" confirms the child [33'48-37']

In this sequence, we see a mother and child spontaneously start to act out CT strategies with the digital tools as part of natural play and engagement with the narrative of the play space (i.e. camping). The analyses of the interactions interrogate when Embeddables both limit and encourage the child's and parent's behavior to engage with the possibilities of CT such as procedural thinking and directional knowledge, and how these key observations might advocate for new interactions in CT technologies.

4.2.1 CT tools using proximity reactions supports procedural thinking

From the above excerpt we can start to see the natural formation of a simple procedural set of actions that targets CT Skills through the guidance of the adult and the narrative of the play space. Although the Embeddables are limited in their ability to continue to propel further exploration, they offer insights into how the proximity coding located in different objects may be able to support further skill development in CT. In the above case, the moment the child holds the Embeddable-rex they begin to form an understanding that this is a different toy as it both vibrates and flashes lights (at this point being close to the foxy and the rabbit). The child, however, does not understand that the vibrations occur because it is in close proximity to the other Embeddables, and starts to walk away with the Embeddable-rex to another location (Line 9–10). When the child moved the Embeddable-rex a little distance away, the vibrations and flashing lights cease, and we see the child stop. From the interaction, it can be surmised that this is because the vibration stops, as the child turns the Embeddable in front of them watching the Embeddable. At this point (Line 11), the mother notices that the child has stopped and is focused on the tool, but having her arms preoccupied, she turns and asks the researcher 'what [do] the toys do?'. After a brief explanation from the researcher (Line 12–13), the mother turns back to the child, she begins by asking if they want to put them together, and instead changes her question and asks, 'where the fox is?' (Line 15). Although it is uncertain why she has self-corrected, the follow up question "*where is the fox?*" sets up a series of actions that begins a game between the mother and the child. When the child locates the fox and places it next to the rex, the child becomes animated, presumably because the -rex has begun vibrating again (Line 21–22). The child then returns the fox and locates the rabbit. Once the rabbit is located and brought over to the rex, the child then repeats the same behavior by systematically moving the tools into the tent. In this sequence, the Embeddables, as a probe, lend themselves to being involved in a game, one based on their interdependent digital interactions and not just their forms. This promotes both digital understanding of the technology and behaviors such as procedural play and social interactions that lay the foundations for higher forms of CT.

4.2.2 Different vocabularies of 'directional knowledge' have implications for instructions

Results show that the Embeddables offer ways for children's adults to explain relationships between digital objects that are connected to their child's play, that young children can understand symbolically rather than technically. The mother initially frames the three Embeddables as 'friends'. After some time, and having developed an initial understanding of what the tools do when they come together, she continues to use the term 'friends' as a way for the child to understand that the tools need to sit next to each other to enable or initiate digitally-controlled reactions "*do you want to* *put the dinosaur next to the fox, because they are friends?"* (Line 17–18). The use of the word 'friends' in the second statement contains a justification of why they sit next to each other "because they are friends" rather than a more technical justification. The child picks up on context, as once the friends are united, they light up and vibrate, causing the child excitedly to exclaim, "*Der's de rah*!" propelling the child to try another Embeddable (Line 22). In this case, symbolic language use paired with both digital and non-digital objects provides important cues for how we might start to fundamentally layer the conceptualisation of digital relationships prior to a more advanced understanding, as this case shows even young children can understand that there are relationships between things. The probe offers the possibility of considering what symbolic language is in line with CT language and how that language can be used when supporting the development of CT with digitised tools, i.e. a system of dependent entities in a group (system) might be conceptualised as friends.

4.2.3 Provide feedback not only to the child but also to a third party

A complicated feature of the Embeddables is that much of the tool's behaviour is not discernable for someone who is not engaging with them. For example, their output feedback is difficult to see from afar, which means the mother must interpret the child's reactions and the language the child uses to describe what is happening. For instance, in lines 21–22 it is difficult for the mother to determine if "Rah!" has a double meaning: 1) 'what a dinosaur says' and 2) 'the vibrations it makes'. In this account, without the mother holding and directly feeling/hearing/observing what they do and why, she can't surmise what the Embeddables are doing or their purpose (inquiring of the researcher present instead). Further development is needed to visualise how objects relate to each other through second-person feedback to ensure children, adults, and educators can build on children's reactions.

4.3 Case 3: embeddables manifest social play

The Embeddables provided moments of social play that were promoted by the interactions of the technology. The younger children in the Children's Museum often played individually with the Embeddables (see Sect. 4.1.1). However, at times, parents intervened or invited them into play and were able to scaffold play opportunities with the children through the distributed nature of the technology in the tools and how the tools interacted with each other. In one example, a child was seen to explore the Embeddables. The parent with the child started to ask the researcher questions about the Embeddables and how they worked. As the researcher sat and explained to the parent, the parent would in turn, show and explain to the young child. The following excerpt is an example from the data of this type of interaction:

The parent turns to the child and says, *"Sit here and touch his arms"*, holding Embeddable-rex. *"Bring it close* [to Embeddable-foxy], *there it goes, touch his hand."* The child holds the arm again to feel the vibrations, but the vibrations turn off. The child turns to Embeddable-rabbit and presses the buttons. *"On, on, on, off, off, off"* says the child as the lights go on and *off, "on, on, off"*. The child then turns back to Embeddable-rex. The parent seeing an opportunity, quickly grabs the Embeddable-foxy, saying *"put those together"*. The child looks up at Embeddable-foxy and continues to press the buttons on the Embeddable-rex. The proximity sensor switches the vibrations on to Embeddable-rex. The parent says, *"There it is… feel it? there it is see it vibrates." "Dah" "Yah do you want to play?"* As the parent holds the hand of the child (Fig. 7), the child utters *"oohh"*. Both sit and watch the lights for a few moments while holding onto Embeddable-rex and foxy. [W5291: 0'47].

4.3.1 Intermittent interactions can be problematic for educators explanations

Case 3 begins with the parent providing instruction to the child "Bring it close [to Embeddable-foxy] … there it goes, touch his hand." (Line 2) The child leans over and touches the hand, but the vibration has switched off, the child becomes distracted by the switching of the LED's on and off "on, on, off" (Line 4). Although in the video we can

Fig. 7 Parent guides child hand to explore the vibrations the Embeddable-rex makes when near the other Embeddables [1′29]

see the child felt the vibrations the first time, from the parent's vantage point they have not been able to discern the feedback from either the child or the Embeddable that the vibrations are occurring and when the child can feel them. This becomes a point of tension for the parent as they continue throughout this session five times to tell the child about touching the hand (see Line 1, 3, 7, 9 &11). The Embeddable-rex's vibrations are just slightly intermittent turning on and off and therefore the parent struggles with understanding if the child has really felt the vibrations. The slightly intermittent nature of the vibrations creates enough uncertainty in the system, that it prompts the parent to continue to explain to the child about the vibrations (See line 7 & 10). Therefore, in further iterations of CT tools, designs should not only ensure that interactions are easily understood from afar but that the system response is clearly displayed when their change i.e. on to off and vice versa, is due to the type of feedback from a triggered interaction.

4.3.2 Young children practice language to describe interactions with technology

In the above case, as the child interacts with the Embeddables, they use language to describe what they are doing when engaging with a simple switch button. The child's use of "on, on, off" (Lines 4 & 5) denotes that they understand that they can turn the LEDs on and off, but also that it is because of their button press that it does so. Switching on and off the lights, although a simple activity often performed by younger children, may provide insights into how children verbalise foundational CT practices through continual accessibility, interaction, and the use of words to accompany those actions. For designers of CT tools, this means providing avenues for young children and adults to co-play, guide interactions and build play narratives to the interactions in a social way.

4.3.3 Embeddables prompt social exploration

As illustrated with the above example, the distributed nature of the technology and the size of the tools provide avenues to prompt social exploration. The child is only able to hold one Embeddable at a time, and therefore the other two Embeddables can be used by the parent to adjust and control the interactions using another Embeddable without needing to take over the device. As an example, in line 6 we can see the parent move Embeddable-foxy closer to Embeddable-rex which is being held by the child "*put those together*" (Line 6 & 7). The child's inability to be able to hold all Embeddables at one time also allows for other children to join in adding a new dynamic to the play and interactions (see Fig. 8). For designers of CT tools, both size and distribution of interactions are important concepts to work with for the social exploration of digital tools.

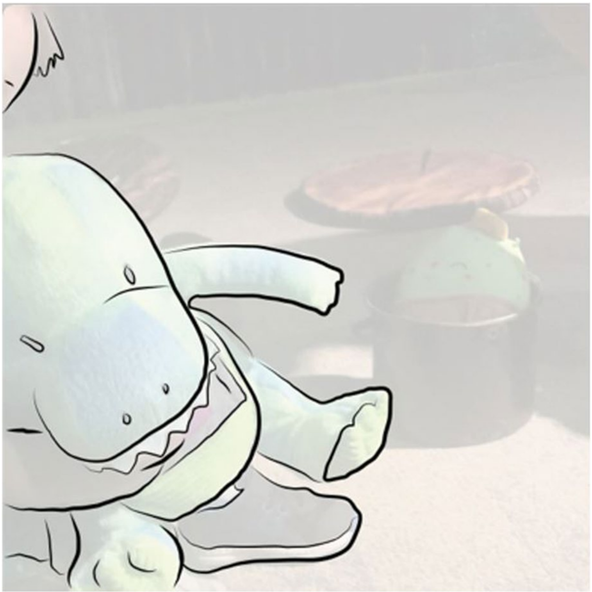


Fig. 8 A child comes over and joins in the play [1′52]

5 Discussion

Wing (2006) reflected that computational thinking, including problem-solving, maths and formal language, is integral to the modern world. CT is an understanding of how digitally embedded humans think through problems that enable machines and others to carry out solutions. From this premise, we have considered learning as a contextually situated activity (Brown et al., 1989; Lave, 1988; Núñez et al., 1999). Our literature review revealed that few studies have investigated foundational activities for CT compared to other areas, such as numeracy and literacy (Su & Yang, 2023). Although unplugged (or non-digital) activities are often used to strengthen CT skill development in younger years (Lin et al., 2023; Saxena et al., 2020), there has been concern, firstly, about the knowledge required for parents and educators to translate these types of activities into CT understandings, and secondly, how children are then able to translate those nascent understandings into working with digital tools as they progress (Grover & Pea, 2013). Issues arise when commercially available digital CT tools developed for older children are implemented in educational environments (informal or formal) for early years. Young children may not be developmentally ready for CT content embedded into these toys, such as perspective shifting and social interactions (Bakala et al., 2023; Critten et al., 2022). The lack of developmentally appropriate resources has led researchers to question whether young children can learn foundational concepts of Computational Thinking with digital tools in the absence of heavily scaffolded, adult-led activities (Avci & Deniz, 2022; Bofferding et al., 2022; Georgiou & Angeli, 2021).

Prior research suggests that for young children to be able to gain skills in foundational CT, the environments and tools need to be supportive of child-led narrative play, as well as provide developmentally appropriate and contextually rich understandings of coding and symbols in a way that matches the children's own understandings of the world (see Sect. 2.4). Specifically, how to couple both the benefits of CT with the developmental abilities of young children is a project that is still in its infancy. Our key observations, however, indicate that in playful environments with simple CT tools, even very young children (18 months) can interact with technologies that engage problem-solving behaviour (e.g. responding to the combination of inputs and outputs beyond actions such as switching on and off a light). Furthermore, when adults intervene, they scaffold what might be described as CT activities, such as framing procedural problems and providing simplified explanations of how technologies work.

In the following section, we discuss our findings in response to our research motivations: to determine how young children and parents incorporate computational thinking in play with novel digital tools (Kotsopoulos et al., 2022) and extract the types of design features from the novel probe that facilitated different CT skills (i.e. Symbolic reasoning, procedural problem solving). We report on the foundational CT interactions observed in the children and outline what we see as the next steps to progress the design CT tools for young (18–36 months) children.

5.1 Exploration of foundational of computational thinking

From our data, there are several ways that CT tools, such as Embeddables, can support foundational knowledge development of CT for very young children below the age of 36 months. Supportive interactions, such as social engagement and using playful body movements to explore the world, are important behaviours prior to gaining knowledge in more complex CT skills (Critten et al., 2022; Odgaard, 2022; Saxena et al., 2020). Likewise, young children who can be developmentally scaffolded (above the age of 4 years), have been shown to be able to begin to form a foundational understanding of CT skills with digital tools, such as procedural thinking and simple directional knowledge (Critten et al., 2022; Saxena et al., 2020; Silvis et al., 2020). Our findings, in line with existing literature on supportive interactions (Social engagement and physical involvement), and readiness for computational thinking (procedural knowledge, symbols and directional knowledge), are discussed.

5.1.1 Supportive interactions: social engagement

Researchers have found that CT activities can be thwarted by the tool's functions and children's preferences for social play in preschool settings (Bakala et al., 2022; Odgaard, 2022). In our key observations, results showed that children (24 – 36 months) would often either pick up the Embeddables to hug or throw and stop mid-play to pay closer attention to their modal outputs. Younger children (18 months) would crawl over to see what the lights were doing to find that the object would also vibrate when it was moved. Adults could respond to their child's curiosity, explaining and demonstrating how the Embeddables worked (Vygotsky, 1980). The initial curiosity was important for instigating the possibility of CT-related conversations where adults could build upon the initial curiosity to explain what was happening inside the Embeddables in an understandable way for the child. For example, in case 2, we see the parent pivoting from the language used by the researcher to a more playful activity of ‘find the fox’, which encouraged the child to explore the interactions by placing the Embeddables next to each other.

The current study also showed that responsive feedback from the tools was an essential attribute of the Embeddables to initiate curiosity and prompt exploration. However, the Embeddables’ sequential feedback was limited. Sequential feedback helps children understand what action to take next or how the technology works (Matthews & Matthews, 2021; Norman, 2013). However, it should also be designed to be a critical (visible) signifier of what is happening with the technology, especially for young children (Bakala et al., 2022; Critten et al., 2022). This study highlights the need for feedback to extend beyond the user and communicate to parents, educators and peers how or why the child responds to the technology in a certain way (Bakala et al., 2022, 2023; Burleson et al., 2018), providing opportunities for social scaffolding. In our analysis, although visual and tactile feedback was incorporated into the Embeddables to give understanding and interest, it was often not enough to explain what was happening in the devices to others. The lack of visual feedback to an adult provided hindrances to understanding what was happening, especially when the adults could not engage with the children’s CT tools themselves, as we can see in case 2 when a mother holding a baby misinterprets the child’s ‘Rah’ because the mother cannot determine that the tool is vibrating when before it was not (line 22 & 23), and in case 3 when a parent misunderstands when a child can feel the vibrations (line 2 & 3). Although research talks about the need for devices to communicate with a third party and the student using purposeful feedback of the system (Bakala et al., 2022; Matthews & Matthews, 2021), little is known about how this can be effectively applied to educational tools designed for young children (under 5). We propose that more work is needed to understand effective communication and feedback strategies for young learners and supplementary support offered to their adults and educators to encourage further social opportunities.

5.1.2 Supportive interactions: physical involvement

For young children, using their bodies in play to explore is an essential method of exploring the world (Ackermann, 2001; Lave, 1988). However, research suggests that very few CT tools are built for free play exploration. They are often built to require educator-led scaffolding of activities focused on mats or tables, restricting children’s agency and ability to use their bodies to learn (Bakala et al., 2023; Burleson et al., 2018; Critten et al., 2022; Odgaard, 2022). Although formal learning is essential in teaching complex CT practices, researchers suggest that tools should also be developed to provide children with opportunities for free play (Kotsopoulos et al., 2022). Providing digital tools to be used in free play for very young children may also support educators in understanding when CT experiences occur and how they can build on these in early learning situations (Kotsopoulos et al., 2022; Odgaard, 2022). This provides designers with an impetus to design tools that encourage gross motor skill development and free play to explore CT skills in the world, in the same ways tools are designed to support language and mathematical development as part of free play and formal learning practices.

Children could take ownership of the Embeddables and incorporate them into different types of play, such as exploration and fantasy play. The interactions made possible through their form, size, and distributed nature of the interactions of the tools allowed for each Embeddable to be interacted with separately and together. As seen in case 2, children would often pick up and walk with the Embeddables one by one to place them in another location. When the Embeddables were in close proximity, children would become excited to see their outputs activated. Adults were often seen scaffolding activities that encouraged the Embeddables to be placed together in a playful way (such as throwing, squishing, or rolling together and further apart), providing an understanding of what types of activities could be done playfully that might lead to further exploration of CT. In this way, Embeddables as a technology probe worked well in uncovering possibilities, however, it was restricted in its inability to provide feedback to adults and encourage longer periods of playful engagement. This could be because the probe was located in a museum where engaging in activities is time-compressed, but as a team we suspect that the digital component of the Embeddables required re-design to extend and heighten the proximity reaction aspect of the tools.

5.1.3 CT Readiness: procedural knowledge

Embeddables showed that dispersed technologies that use proximity reactions can orchestrate activities that promote procedural thinking. In case 2, a parent watched their child's reactions as they took possession of an Embeddable that vibrated only to find out that it stopped working as soon as they did so. They encouraged the child to, one-by-one, look at what each Embeddable did: firstly, with Embeddable-foxy, then Embeddable-rabbit, and then finally all three. The child then imitated this behavior moving the Embeddables into a play tent nearby (see 6e). Odgaard (2022) discusses that CT tools are often thwarted by children aged 4–5 years in preference of social play and are frequently used as push button tools or picked up and moved without engaging in CT behaviour. However, our findings suggest that tools such as Embeddables can support a more playful understanding of procedure when coupled with critical inquiry exploration by the parent. The attributes of Embeddables that allowed them to be used in a procedure-type activity stem from their inherent proximity interactions that are not decipherable until they react differently in proximity with each other, therefore finding out what each Embeddable does encourages exploration of how each one works (see Sect. 4.2.1). The use of familiar characters and referring to the tools as 'friends' also encouraged the children to engage their developing theory of mind as a conduit to developing their CT, to consider that relationships between the tools exist and to explore the nature of those relationships (Sodian et al., 2020).

5.1.4 CT READINESS: symbols and directional knowledge

Symbols and directional knowledge are fundamental in understanding CT. Currently, research has shown that although these two CT skills are important, blending spatial directional knowledge with an understanding of symbolic coding is complex and difficult for children younger than 5 (Silvis et al., 2020). Directional knowledge however is integral in understanding the symbolic code used in many vehicle-based CT tools such as Bee-Bots and Cubetto. Similarly, Critten et al. (2022) found that when young children (under 4) were using directions on maps or to be able to program Bee-Bots that children's views of movement in the world did not align with those that required directional movement from an alternative perspective, however, the older children (4–5 s) were able to start to make sense of perspective differences between them and the robot.

In the video data, adults often were heard asking children to move objects next to, close, or together to enable objects to 'work'. Directions were given from the perspective of the child, but were enacted via the tools, providing a more developmentally appropriate use of directions in the domain of computation. The adult's ability to tie directional language to the interactional movements of digital devices also supports the child's metacognitive ability in the use of symbolic language to what is happening within the technology. An example of this is in Case 3, where a young child can be seen to verbalise 'on, off' as they engage in pushing a switch. These findings provide insight that digital CT tools can support a more fundamental directional knowledge and use of symbolic language for younger students that are tied to attributes of the technology. Further studies are needed to determine the types of alternative relational (or 'proximity') designed tools that can scaffold the development of conceptual knowledge, needed for the blending of symbolic coding and perspective shifting that are necessary to the further development of being able to code tools (i.e. vehicle robotics).

5.1.5 Possibilities for tools in developing conditional logic and pattern definition

As can be seen in Table 2, we see possibilities for alternative thoughtful CT tools to support further foundational understanding of conditional logic and pattern definition. Researchers have discussed that young children have shown understanding of NOT blocks through interacting with coding blocks situated in the world (Wyeth & Wyeth, 2001). The combination of both symbols and proximity reactions in CT tools presents possibilities that could lead to the construction of more complex conditional logic. We also found other potential opportunities for gaining CT skills that could not be fully realised with Embeddables as a technology probe, such as the potential to explore further communication of the problem and pattern definition. Case 2 showed the most promise, demonstrating that it was possible to develop patterns, however, this was simplified and only occurred rarely in our data.

5.2 Exploring alternative methods for exposure to coding concepts.

As researchers have pointed out, there are underexplored opportunities with how best to support young children's understanding of computational thinking (Silvis et al., 2020). We took the approach of building a novel technology probe and deploying it in a children's museum to observe how young children explore CT tools. In this study we found that there was a lack of clarity for users in how Embeddables worked as a technology probe to support play with coding behaviors and the development of CT

Table 2 Overview of Findings for the potential design of CT tools

Supportive interactions	Inquiry for the design of CT tools	CT Development for 18 – 36 Months
Fine motor skills		Not seen
Social interaction	Disperse interactions between multiple devices Choose size that complements purpose (i.e. one child per one device with interconnectivity or multiple users) Offer multiple levels of feedback that encourage both children and adults understanding of interactions	Individual play, and play with adults (see Sect. 4.1, 4.2 & 4.3)
Physical involvement	Create objects that are able to be carried, thrown, rolled ontop of without injury. Robust	Proximity coding was able to be acted out and supported through bodily movement (see Sect. 4.2) with support of adults
Communication of problem		Not seen
Readiness for computational thinking	Design guidelines	CT Development For 18 – 36 Months
Procedural Thinking	Create interactions that are displaced, but that also allow appropriate inputs and outputs to be mentally connected together through iteration i.e. switch and light bulb Consider the types of activities with tools	Proximity coding was able to proceduralised with support of adults (see Sect. 4.2)
Knowledge of CT symbols	Consider form and interaction to support 'in world' knowledge building	Readiness to learn (see Sect. 4.2 & 4.3). Evidence shows that children understand on, off, next to, etc.
Debugging		Not seen
Conditional Logic	More exploration needed. However, evidence suggests that with using familiar symbols and proximity coding that it could be achieveable in young children	Evidence shows the beginning of exploration for Case 2 (see Sect. 4.2)
Defining Patterns (algorithmic thinking)	More exploration needed	Evidence shows a beginning pattern of behaviour for Case 2 (see Sect. 4.2)
Direction Perspectives		Foundational: next to, close, together

through proximity reactions. Children's interactions with the probes prompted questions from adults of how the proximity reactions worked together, but there was very little evidence of children actively manipulating the proximity sensors in the tools to change output behaviour on their own accord. However, what was witnessed, was adults providing cues for children to help them uncover how the technologies worked together after seeing how children experimented with the technologies in their play. This opens several avenues for further inquiry. It may be that the action-at-a-distance nature of proximity reactions is an abstraction that young children may not easily grasp, or that the indefinite boundaries of interaction are a confounding factor with respect to manipulating how the Embeddables can be made to react to each other. This may point to the need for better design with respect to feedback and feedforward (Matthews & Matthews, 2021), or the incorporation of interaction rules (van Huysduynen et al., 2016). In the next steps, we will be exploring additional methods of designing coding behaviour for children to discover and manipulate interaction, and to comparatively determine how older (3–5 years) children respond to, play with, and understand the Embeddables.

In answering our research questions: how young children and parents incorporate computational thinking in play with novel digital tools (Kotsopoulos et al., 2022) and extract the types of design features from the novel probe that facilitated different CT experiences (i.e. Symbolic reasoning, procedural problem solving), we developed a technology probe that incorporated features such as proximity reactions, multi-modal interactions, distributed system across several characters, and playful tactile characters. Our technology probe was placed in a children's museum where we were able to observe the types of activities children (18 – 36 months) and their parents gravitated to when interacting with the devices, such as crawling and throwing the probes together to create unexpected moments that led to exploring the devices (case 1), proximity games facilitated by parents (case 2), and social play through a distributed system of technology in tools (case 3). From our field observations, we were then able to consider how such activities lead to supportive interactions and CT readiness skills outlined in the literature, and what design features supported or obstructed these skills. The design features are summarised in Table 2 and extend existing literature in understanding how digital tools can support very young child-adult discussions and explorations in fundamental understandings of CT through foundational processes of symbolic language use, procedural thinking, supporting of directional perspectives and physical interactions.

5.3 Limitations & practical research suggestions

There are two main limitations of this study. Firstly, our results are based on interactions in a children's museum, which 1) reduces the amount of time participants have with the devices as there are always other activities to explore, 2) play with the devices are not always focused, 3) museums are not an everyday environment for young children compared to preschool or home settings, (although provides a broad demographic of participants).

Secondly, the study was performed in one session. Multiple sessions would provide a better understanding of how children would adapt to the technology probes in play.

To address the above issues, future work will include iterations on the devices from our findings, including implementing more complex conditional elements and more salient sequential interactions (see Table 2 and Fig. 1). Subsequent devices will be placed in preschool contexts where children will have longer play sessions with the tools.

6 Conclusions

To date, there has been a minimal understanding of what young children (18 – 36 months) can learn with digital tools through social scaffolding and digital exploration of the fundamentals of Computational Thinking (Chu et al., 2024; Gerosa et al., 2021; Yu & Roque, 2019). Many existing digital tools have been found not to offer developmentally appropriate methods to support the development of CT skills with or without educator-led scaffolding (Critten et al., 2022; Newhouse et al., 2017). Furthermore, with very few interaction modes available in existing digital tools, research must examine how different kinds of CT tools with novel interactions and interactivity support building CT fundamentals and/or the foundational knowledge needed for CT skills, particularly when in a supportive context and with appropriate adult/peer support (Gerosa et al., 2021; Yu & Roque, 2019).

This paper explored a novel technology probe developed in response to our research question: how do young children and parents incorporate computational thinking in play with novel digital tools, and what design features from the novel probe facilitated CT experiences? Our research question was developed from literature discussing the need to provide opportunities for young children to explore digital CT technologies, which are non-screen-based (Erstad & Gillen, 2019; Sullivan & Strawhacker, 2021). We found that currently, few tools have been designed or referenced in terms of how they can support young children's engagement with CT.

The novel probes were implemented into a museum space, and our data analysis determined features of digital devices that supported social interaction, play and CT exploration of digital CT tools. **Social requirements** were supported through features such as sequential feedback with visible signifiers, which helped knowledgeable others understand the 'state' of the probes, providing guidance and direction to young children. The children explored **physical, playful interactions** with the probes. Most CT tools are placed on tables and floors, which do not consider how children use their bodies to explore their world (Bakala et al., 2023). We found that the plush and the proportion of the tool features supported children's desire to throw, roll, and walk around with the Embeddables, providing avenues to explore. Lastly, we found that the Embeddables provide avenues to explore foundational CT experiences such as **directional perspectives, symbolic language use, and procedural thinking**. From our findings, the proximal interactional features supported symbolic language use of directional (close, near, far) rather than movement instructions (i.e. left, right) and may provide young children opportunities to practice symbolic spatial knowledge building and procedural knowledge, which form core foundational CT experiences and are more in concert with young children's developmental needs (Clarke-Midura et al., 2024; Gerosa et al., 2021).

In conclusion, this project presents a considered approach to how design can support young children's explorations of CT through screen-less digital tools.

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Data availability The authors confirm that portions of analysed data are included in this paper. The sensitive nature of our work means that we do not publicly share all available data.

Declarations

Competing interest No potential conflict of interest was reported by the author(s)

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