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Research Paper

Social and curious: Lessons in designing digital manipulatives for young children

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ABSTRACT

Introducing Digital Literacy (DL), including Computational Thinking (CT), to young children develops foundational skills in computer science, problem-solving, and critical thinking. However, current digital toys for demonstrating computational thinking strategies are not always designed for early-year environments or specifically for young (preschool) children. Digital manipulatives incorporating embedded computation can offer developmentally appropriate tools to introduce foundational programming strategies and dynamic system knowledge before children become developmentally ready for more formalised programming activities. This paper presents an empirical study in a preschool environment with children (aged 3–5 years) using novel digital manipulatives, *Embeddables*, in child-led free and guided play activities in a preschool (Fig. 1). From our analysis of the types of activities the children engaged in, we identified underexplored design features of digital manipulatives that can build early exposure to CT skills through ludic and epistemic play. These are designed-in behaviour, distributed interactivity, conditional and proximal relations between artefacts, and abstracted multisensorial reactions.

1. Introduction

Children are now growing up in a digitally saturated world; not only do they need to comprehend the physical and spatial relationships between objects in the physical world, but they must also learn to navigate digital possibilities and interactions hardly imaginable a generation ago. In many parts of the world, children now have first-hand experiences of the digital world before they can speak more than a few words. It is widely acknowledged that early interventions that provide children with opportunities to understand, create, and command digital technologies lay the foundational groundwork for the development of more complex ideas and skills (Grover & Roy, 2013; Resnick, 2008). Early years educators introduce developmentally appropriate tools (i.e. blocks, toys, and buttons) to provide learning opportunities that enable young children to take small but important knowledge leaps. Such early interventions have led to positive learning experiences with, through, and about digital technologies, developing self-efficacy in emergent computer literacy competencies, including Computational Thinking (CT) (Okal, Yildirim, & Timur, 2020). Yet many of these tools are not specifically designed for preschool children or informal play-based environments; instead, they are primarily intended for use in formal classrooms in the first years of primary school, with children at higher developmental stages. The scarcity of tools for this specific young age group and learning environments creates a deficit of understanding of what children can learn through play with digital technologies (Bird & Edwards, 2015; Critten, Hagon, & Messer, 2022; Erstad & Gillen, 2019; Newhouse, Cooper, & Cordery, 2017). Yet CT ought to be seen as an emergent process, similar to other learning areas such as reading, writing, and mathematics (Erstad & Gillen, 2019). As active meaning makers, young children build the foundations of understanding

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technology by interacting (socio-culturally) with toys without direct or formalised instruction (Brown, Collins, & Paul, 1989; Erstad & Gillen, 2019; Jean, 1988; Vygotsky, 1980; Wertsch, 2009). This is tightly coupled with research into how young children learn with digital technologies through child-led play (ACECQA, 2022; Bird & Edwards, 2015; Newhouse et al., 2017).

Digital tangible toys incorporating embedded computation are a notable subset of educational technologies that provide unique opportunities for children to explore how technology works in concrete and abstract ways (Manches & O'Malley, 2012; Resnick et al., 1998, pp. 281–287). Digital tangible toys differ from other types of digital toys in that they 1) are self-contained, i.e. they do not need to interface with an external computer to download code or for remote control; 2) communicate responsively with their environment through sensors, Wi-Fi, radio or Bluetooth (Bakala, Gerosa, Hourcade, & Tejera, 2021; Raffle, Parkes, Ishii, & Lifton, 2006); 3) employ physical movement as a programming strategy. Digital manipulatives' ability to communicate responsively to each other and their environment makes them ideally suited as an early interface to demonstrate CT strategies (Bakala et al., 2021; Resnick et al., 1998, pp. 281–287).

In this paper, we introduce novel technology probes – *Embeddables* (see Fig. 1), a type of Digital manipulative with embedded computation. The technology probe was designed with children aged 3–5 years in two preschool classrooms. The *Embeddables* are programmed microcontrollers, small vibration motors, and LED arrays inset into plush toys to make them digitally interactive.

In our study, we show how digital manipulatives with embedded computation, such as Embeddables, offer a promising approach to developmentally appropriate tools for introducing young children to foundational interaction strategies and dynamic feedback systems in preparation for more formalised programming activities (Critten et al., 2022; Gerosa, Koleszar, Tejera, Gómez-Sena, & Carboni, 2021). Technologies like *Embeddables*, which promote children to experiment and explore technology with their bodies, occupy a space between the immediate cause-and-effect of everyday technologies (such as light switches) and more abstract coding strategies that require perspective-shifting and/or three or more steps in a problem-solving task (Critten et al., 2022; Gerosa et al., 2021) (see Section 2.3). Our study addresses the research question: How might digital toys be designed to support social and child-led (aged 3–5) play while building early exposure to CT?

2. Literature review

In Australia, digital literacy contributes to a holistic education in early childhood pedagogy (ACECQA, 2022). Digital literacy, which builds on computer literacy, encompasses an extensive array of activities, including social media use, reading on digital platforms, and digital technologies to solve problems (Santos & Gomes, 2024; Ruthven, 1984; Van Dijk, & Van Deursen, 2014) (the latter of which is the focus of this paper). The importance of digital literacy as a new component of the early years' curricula and as a general (rather than specialised) competency places a particular responsibility on designing tangible digital literacy tools for young learners. Digital literacy involves children's ability to take action through decisions and embodied physical actions with technology (Erstad & Gillen, 2019; Newhouse et al., 2017). Digital literacy, when applied to tangible (non-screen-based) programmable technologies, often involves forms of problem-solving and social meaning-making in early childhood environments, which are components of CT (Jeannette, 2011; Kafai, Proctor, & Lui, 2020; Newhouse et al., 2017). CT is a broad evolving term, and in this paper, our current working definition is derived from Wing's (Jeannette, 2011; Wing, 2006) discussion on CT, which is that: CT is the exploration, synthesis and solution-finding process to solve complex (including open-ended) problems that take into account human behaviours and communicate a solution in a way that allows for scalability and complexity (abstraction), to enable either a human or machine to be able to implement (Gerosa et al., 2021; Grover & Roy, 2013; Louka, & Papadakis, 2023). Because of the breadth of activity needed to develop CT, researchers have typically broken CT down into skills (discussed in Section 2.1). In this section, we map the design of digital toys to scaffold digital literacy in early childhood environments to increase exposure to CT and their ability to support child-led play.

2.1. Employing embodied cognition guidelines in the design of tangibles

The understanding that there is a strong link between activity (physically bound by time) and how we assimilate knowledge of the world has profound implications for child-computer interaction research, including how we design objects for young children with developing knowledge-building capacities (Ale, Sturdee, & Rubegni, 2022). Embedded Cognition seeks to explain the relationship between the body, mind and the world, and how, through interacting with the world (socially, culturally and in context), we assimilate knowledge (Jean, & Wenger, 1991; Núñez, Edwards, & Matos, 1999; Varela, Rosch, & Thompson, 1991). Embodied cognition understands our conceptual, knowledge-building systems in the world in several ways: as a situated activity (knowledge is built as part of the context in which it is performed) (Núñez et al., 1999; Wilson, 2002); as a dynamic activity (occurs in real-time in the world and therefore requires evolving processes and problem-solving (Anderson, 2003; Wilson, 2002)); as a responsive activity, able to discern between relevant and irrelevant information, and strategically cognitive offload information when needed (Anderson, 2003).

Embodied cognition builds on earlier notions such as Husserl's 'lived world' and Heidegger's 'being-in-the-world'; it acknowledges the importance of the body—including movement, sensory exploration and lived experience—in the scientific inquiry of 'how we come to know', and indeed consciousness (Varela et al., 1991). In particular, Merleau-Ponty built on Husserl's insights to recognise both the 'lived-world' experience of the body and the transformation of the internal biological world are essential and mutually dependent, creating a reflexive cyclical knowledge-building system. This does not position either the cognitive or 'lived-world' experience as dominant, but posits a reciprocal knowledge-building system (Varela et al., 1991).

Child Computer Interaction (CCI) researchers have combined embodied cognition and education theory to support the designer's conceptualisation of systems that engage and encourage meaningful activity connected to the world (Alissa, 2007, pp. 195–202; Marshall, Price, & Rogers, 2003, pp. 101–109; Núñez et al., 1999). Frameworks and principles provide guidelines for designers, such as Antle's CTI framework (Alissa, 2007, pp. 195–202) (or, e.g. Hornecker and Buur's Tangible Interaction Framework (Hornecker & Jacob, 2006)). Antle's framework was built in consideration for children between the ages of 4–12 and includes five themes: space for action (supporting physical actions to control systems and providing avenues for epistemic play (exploring how things work)); perceptual mappings (connecting the physical to the digital through affordances (see also conceptual metaphors (Manches & O'Malley, 2012)); behaviour mapping (Alissa, 2007, pp. 195–202) (examining the relationship between input and output behaviours, highlighting the role of reflective, cyclical knowledge building in embodied cognition (see also process-related feedback that

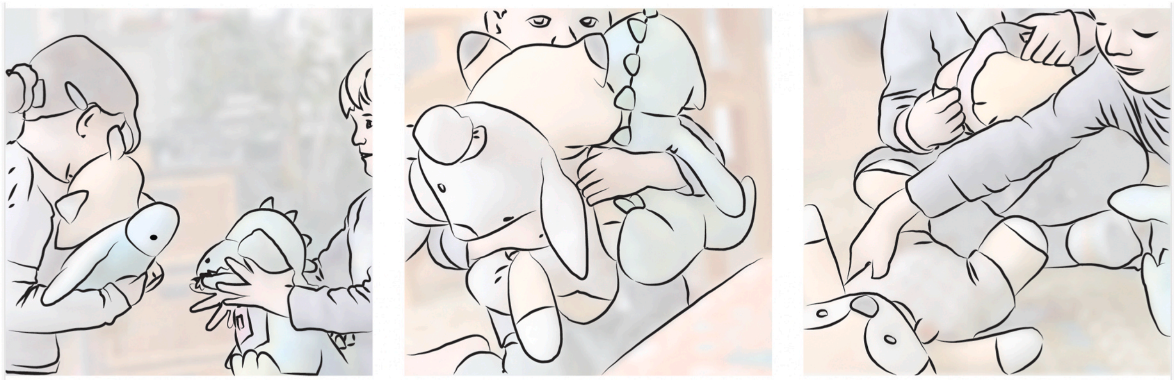

Fig. 1. Three images of a technology probe, Embeddables, in child-led play in a preschool.

promotes debugging (Matthews & Matthews, 2021; Resnick & Silverman, 2005, pp. 117–122))); semantic mappings (Alissa, 2007, pp. 195–202) (ensuring interactions are meaningful to children and the context in which they exist); and space for friends (providing multiple input units to support collaboration (see also (Hennessy & Murphy, 1999)). Guidelines[1] orient designers of technologies to considerations that can help facilitate embodied interactions and lead to constructive outcomes in situated activities.

2.2. Grid-agent models and dominant interaction paradigms for digital toys

Early Childhood Education involves both informal and formal learning. Informal learning focuses on children's learning skills that benefit the whole child and supports them to become 'school' ready. In Australian preschools, informal learning environments predominantly focus on child-led play, where children are encouraged to explore the world at their own pace (ACECQA, 2022). Formal learning supports children in developing skills in more specialised domains, such as letter writing or specific science experiments, and is often conducted with scaffolded teacher-led play.

Programmable digital toys aim to develop CT in early formalised education (foundational to year 1). Digital toys that are prevalent in research often utilise one of two user interfaces: those with control buttons (i.e., BeeBots) or those that use blocks/cards of code to control vehicle robots (i.e., Alert, Electronic Blocks, Kibo, Botley, Bluebot, Cubetto) (Gerosa et al., 2021; Yu & Roque, 2018, pp. 289–299). Both interfaces rely on activities with directional commands, described as 'grid-agent models', that is, tangible robots that utilise grids for coding activities (Clarke-Midura, Lee, Shumway, & Hamilton, 2019). Digital toys used in CT activities are reported to support young children's skills in debugging strategies, understanding conditional statements, identifying patterns, and creating simple algorithms (Gerosa et al., 2021; Grover & Roy, 2013). These same tools and activities are often replicated and given to younger children without understanding the differences between age groups and learning environments. Research into the educational impacts of these devices has found that these digital toys rely on concepts still developing in these younger age groups (Critten et al., 2022; Saxena, Lo, Foon, & Wong, 2020; Su & Yang, 2023). For example, research has found that perspective shifting (Clarke-Midura et al., 2019; Critten et al., 2022), developing three-step instructions (Saxena et al., 2020), algorithmic mathematical abstractions (i.e. ↑3 + →4) (Clarke-Midura, Silvis, Shumway, Lee, & Kozlowski, 2021; Lodi & Martini, 2021), and defining patterns (Saxena et al., 2020) are often problematic when young learners use existing digital toys. In Table 1, we show current research in the field of education that reports on the types of activities children can do with digital manipulatives. Findings across these studies show that little is known about what children can or cannot do between the ages of 3–4 years with digital toys. Between 4 and 5 years, researchers report that some children can achieve some of the tasks designed with digital toys and are developing strategies.

2.2.1. Alternative interfaces for digital toys

Critten, Hagon, & Messer (2022) explored how young children (aged 2–4 years) can perform CT activities with and without adult-led play. Results showed that children as young as four years can learn through robotic-type digital toys like Bee-Bots but need 1-to-1 educator support. Although this indicates that young children can learn CT activities with these types of grid-agent robots , it also highlights that in informal environments where child-led play is the predominant method for learning, other types of devices might be better suited. Researchers in this area have pointed to the lack of resources and studies incorporating other interfaces (Bakala et al., 2021; Yu & Roque, 2018, pp. 289–299) that may offer more appropriate ways of involving children in developing foundational CT skills, such as audio, gesture, and physical programming (Bakala et al., 2021; Clarke-Midura et al., 2019).

Two other interfaces that don't rely on grid-agent robots are 1) Digital manipulatives that incorporate embedded computation and 2) open-ended digital toys with coding elements (Bakala et al., 2021; Frei, Su, Mikhak, & Ishii, 2000; Yu, Zheng, Tamashiro, Gonzalez-millan, & Roque, 2020, pp. 453–459). Digital manipulatives that incorporate embedded computation rely on programming or manipulating the behaviour of a toy to change its output (Raffle et al., 2006). An example of this type of interface is 'curlybot' (Frei et al., 2000). The curlybot is aimed at ages four and up and offers a physical-experimental understanding and a playful approach to differential geometry. The authors hypothesised that this type of digital manipulative could provide a new kind of tangible for learning with young children by including a manipulative that did not use screens or knowledge of formal coding but, through manipulation, could change the robot's behaviour (Frei et al., 2000). This ability to use non-traditional (and non-abstracted) modes of interaction to control and explore a specific concept gained traction. In more recent research, several other projects have used similar strategies to explore how computation can be embedded into the physical interactions of system devices (Bekker, Sturm, & Berry, 2010; Marshall et al., 2003, pp. 101–109). Such system devices enable children

[1] There has been a growing body of research in the design of tangible digital toys for educational purposes. Design principles such as 'low floors and wide walls' are intended to ensure that novices can quickly get involved and have room to develop and grow (Resnick & Silverman, 2005, pp. 117–122). Other principles include incorporating process-related feedback that promotes the child's ability to debug (Matthews & Matthews, 2021; Resnick & Silverman, 2005, pp. 117–122), and collaboration opportunities for social learning such as supporting multiple hands (Hennessy & Murphy, 1999). However, these well-known principles were developed for school-aged children and in formal learning environments. A question remains about how these principles must be considered and re-evaluated for early childhood education.

Table 1
An overview of research outcomes that have explored digital manipulatives for exposure to computational thinking conducted with children aged 3–5 years.

Readiness for CT	Digital Toys	3–4 years CT Research	4–5 years CT Research
Procedural thinking (creating an algorithm): Being able to plan or communicate a procedure to perform a task (Critten et al., 2022; Grover & Roy, 2013; Saxena et al., 2020)	Bee-bot (robot with buttons) (Critten et al., 2022)	Not yet visualising multiple steps with Bee-bot (Critten et al., 2022; Saxena et al., 2020)	Developing, some children can complete three step instructions for robots (Bers, 2010; Critten et al., 2022)
Knowledge of CT symbols: Understanding what symbols mean and how they show different concepts (Critten et al., 2022; Grover & Roy, 2013; Saxena et al., 2020; Wyeth & Wyeth, 2001).	Bee-Bot (robot with buttons) (Critten et al., 2022), Electronic blocks (stackable blocks with input and outputs) (Wyeth & Wyeth, 2001)	No evidence. Should see developing knowledge of symbols	Limited evidence. Should see developing knowledge of symbols (Critten et al., 2022)
Debugging (Bakala et al., 2022, pp. 422–429; Misirli & Komis, 2023): Finding where the problem is when manipulatives or manipulatives in activity are not behaving as they should.	Bee-Bot (robot with buttons) (Misirli & Komis, 2023)	Unknown	Developing. Trouble with locating the observed problem in the code (Misirli & Komis, 2023; Silvis, Lee, Clarke-Midura, Shumway, & Kozlowski, 2020). Can begin to debug the technology (Silvis et al., 2022)
Conditional logic (Grover & Roy, 2013; Wyeth & Wyeth, 2001):	Electronic blocks (stackable blocks with input and outputs) (Wyeth & Wyeth, 2001)	Unknown	Developing in understanding of 'toggle' switches and 'not' blocks (Wyeth & Wyeth, 2001)
Defining patterns (abstraction and algorithms): Seeing patterns, recognising code 'loops' (Saxena et al., 2020)	Bee-Bots (robots with buttons) (Saxena et al., 2020)	Developing (with Bee-Bots (Saxena et al., 2020; Bers, Flannery, Kazakoff, & Sullivan, 2014))	Developing (with Bee-Bots (Saxena et al., 2020; Bers et al., 2014))
Spatial thinking (direction/perspective shifting) i.e. taking on the perspective of the robot as distinct from the child's perspective and mental appropriation (Bakala et al., 2022, pp. 422–429; Clarke- et al., 2021a; Saxena et al., 2020)	Bee-Bots (robots with buttons) (Anzoátegui, Pereira, & Jarrín, 2017) Kibo, (robots, sensors and code blocks) Botley, (robots with cards) (Bakala et al., 2022, pp. 422–429) Robotito (robot with clour cards) (Bakała et al., 2019), Bluebot. (Robots with buttons and code cards) (Bakala et al., 2022, pp. 422–429) Cubetto (robots with code tiles) (Anzoátegui et al., 2017)	Not yet	Developing but with 1 to 1 support (Critten et al., 2022; Saxena et al., 2020)

to explore through physical interactions and, in doing so, create an understanding of complex systems using real-world knowledge (Grover & Roy, 2013; Jeannette, 2011; Manches & O'Malley, 2012).

Open-ended toys with coding elements have supported more child-led approaches. However, little is known about how young children understand and incorporate the coding elements in their play with these devices. An example of this type of device is CodeAttach (Yu et al., 2020, pp. 453–459), an open-ended platform consisting of a hardware device that outputs sound, LED lights and vibrations, an app for coding, and Velcro that allows the hardware to be attached to different items. Children can create a plaything without relying on directional skills, which has advantages for young children.

Unfortunately, none of the above projects has been implemented in informal preschool environments; therefore, it remains unknown how different types of interfaces facilitate engagement and exposure to CT with technology in child-led play. More work is needed to determine if other types of digital toys can offer more developmentally appropriate ways to encourage digital literacy, such as problem-solving through debugging and setting out a procedure of action.

2.3. Striking a balance between child-led social play and educational outcomes

Play is essential to young children's development and is an important pedagogical tool to encourage exposure to a range of skills focused on embodied knowledge of cause and effect rather than abstract concepts (Bruner, 1996). For digital literacy in the early years, play provides a low-risk avenue for children to try, test, and apply knowledge through different activities and social connections (Vygotsky, 1980). In educational environments, play can be free or guided (adult or peer-supported); however, play must be child-led and explorative, providing opportunities for teachers to encourage and extend (Kaup, Møller, & Brooks, 2023, pp. 95–112; Hewes, 2006).

For early childhood environments, the design of digital toys to create educational opportunities must accommodate child-led play and incorporate embodied knowledge of the world into free and guided play environments. Most education about digital technologies in primary schools and pre-schools is undertaken through scaffolded activities. In a systematic review, (Kaup et al., 2023, pp. 95–112) reported that this is partly due to the complexity of the subject and the need for further training of educators to highlight when skills such as Computational Thinking are practised. Other researchers have highlighted the features of the design of the toys that promote semi-structured activities over free play. For example, Odgaard (Odgaard, 2022) investigated how CT outcomes can be circumvented by the features of the tool when there is a reliance on educator-led activities, especially in the early years (foundational to grade 2) classrooms, as there is often one educator to 20+ children. When teachers' attention is diverted, existing digital toys can be overridden (i.e., handled) by children's desire for social compliance in wanting to play with peers or perceived by the educator as doing the right thing, resulting in reduced time with digital tools in CT activities. The current study raises important considerations regarding the design of digital toys for use in early-year classrooms and their ability to accommodate the priorities of children's desire for social acceptance and open-ended play whilst maintaining educators' priorities of developing exposure to CT.

2.3.1. Design considerations for informal early education environments

Preschool child-led environments are active and hands-on, encouraging children to use objects through social play (Bird & Edwards, 2015). Bakala, Pires, Tejera, & Hourcade (2023, pp. 477–486) interviewed teachers to understand what happens when digital toys for CT activities are brought into early childhood classrooms. One of the main criticisms levelled at the design of existing toys was that devices are often designed for individual use. Therefore, educators' classroom objectives of needing to have inputs and outputs visible to others or being able to divide roles between devices are not realised (Bakala et al., 2022, pp. 422–429). A second consideration raised in the research is that digital toys are often considered 'fragile'; if children stepped on or dropped the devices, they would sometimes break. Likewise, many components were irreplaceable and were frequently lost in the bustle of the day. Therefore, when devices were used, they were always used with an educator and up at tables, limiting the children's embodied play (Lee, Joswick, & Pole, 2023). Thirdly, educators needing to upload codes organised through the sequencing of blocks was seen as problematic. Children often lack an understanding of the purpose of placing coding blocks in a 'sequence of actions' and, therefore, require input from educators to fix their code (Bakala et al., 2021). To the extent that these remain open challenges for the design of tangibles for older (school-aged) children, such challenges are only magnified for younger learners.

2.3.2. Framing digital educational outcomes through play

The importance placed on child-led play and the tools that support and facilitate those activities has been actively discussed in early childhood environments (Bird & Edwards, 2015; Hewes, 2006; Newhouse et al., 2017). As young children engage with activities with tools, their activities develop and change, creating opportunities for further education (ACECQA, 2022; Hewes, 2006). Bird and Edwards (Bird & Edwards, 2015) developed a digital play framework to unpack how children learn about technologies through play. Based on Vygotsky and Hutt's work, the framework highlights the relationship between the cultural context and activity, i.e., as children's skills develop with the tool, the activity also changes (Vygotsky, 1980), and the types of play, including activities that support children in understanding what the object does (epistemic) and how it can be incorporated into play (ludic) (Bird & Edwards, 2015).

The framework was used to analyse how young children aged 3–5 years appropriate CT tools, including BeeBot (Bee-Bot. Retrieved October 13, 2024) and Sphero (Sphero Central, Retrieved October 29, 2024) toys, in their play. Newhouse et al. (Newhouse et al., 2017) found that although young children could continue to develop proficiency with the software and hardware, planning and executing an algorithm with the toys was not visible in children's free play and only happened in scaffolded sessions. Children also tended to spend very little time understanding, planning or using the BeeBots and Spheros in play, with only a few exceptions. This research project shows that there are a lot of positive aspects to incorporating existing digital technologies into a play-based environment. However, existing expectations of educational outcomes need to be tempered with what children can reasonably be exposed to in play from such devices. The current study seeks to provide a baseline for understanding the tradeoff that needs to happen between the types of digital literacy and the different kinds of playful activities that can be achieved in epistemic and ludic play perspectives.

2.4. Summary and research gap

From this literature review, open questions remain as to how tangible toys for digital literacy might better support children in child-led, playful activities and social interaction. Findings from this literature suggest that programming blocks and tangible robots that promote step-wise problem-solving are the predominant types of digital toys currently used by researchers and educators. However, the successful development of some CT skills has not yet been demonstrated with such devices, even in scaffolded activities involving perspective shifting, multiple-stepped problem-solving, and understanding symbols. Consideration of embodied cognition invites design to explore the connection between mind, body and environment in developing lived experiences. Yet types of digital toys that foster social, open-ended problem solving, in balance with both free and guided play activities, are currently underdeveloped and under-explored (ACECQA, 2022; Odgaard, 2022; Clarke-Midura et al., 2019) especially given that few studies implement digital (tangible) toys in early childhood settings (Frei et al., 2000; Raffle et al., 2006). The lack of available observational data in early-year classrooms limits the design field's understanding of the usefulness of such tools. This has a cumulative effect by supplying educators with tools that are not always fit for purpose (Gerosa et al., 2021) and the continuing documentation of problems with existing technologies (Bakala et al., 2022; Bakala et al., 2023; Odgaard, 2022; Critten et al., 2022). As such, the research reported in this paper is guided by the following research question:

RQ: How might digital toys be designed to support social and child-led (aged 3–5) play (ludic and epistemic) while building early exposure to CT? The study outlined in this paper considers (a) Digital manipulatives that incorporate embedded computation in child-led free and guided play and (b) exploring alternative embedded behaviours of tools that might support their playful activities.

3. Methodology

A research-through-design process with children (aged 3–5 years) was conducted at a rural Australian preschool. Our overall approach involved observing how young children understand the tools given in an environment familiar to them, analysing issues with a team of educators, designers and computer scientists to provide insights (Section 3.1), followed by an iterative process of designing, prototyping, and deploying in the field. A bespoke technology probe was built to consider how a digital manipulative might be designed to support social and child-led (aged 3–5) play while building early exposure to CT.

The following features were included: open-directional and multimodal interactions, simple conditional coding, a distributed system that contains proximity reactions, and plush playful forms (see Section 3.3.1). In deploying the technology probe in a preschool, two cameras—one roving and one fixed—captured video data. The research team analysed the video data using interaction analysis (see Section 3.4). The focus of the analysis was to first understand how digital manipulatives were incorporated into play activities by children and, second, how these activities might lead to a concrete understanding of foundational coding strategies and dynamic systems.

3.1. Observational studies in preschool

Observational studies were conducted in an Australian regional preschool in a small town (population ~4000) approximately 1 hour's drive from a metropolitan centre. Prior to this study, the preschool had not engaged with tangible educational technologies, although they often used wall-mounted touch screens and personal computers to search for answers to children's questions and watch educational media.

In response to our research question (see Section 2.4), we opted for a qualitative study with a targeted sample of participants to investigate our phenomena in depth (O'Reilly & Parker, 2013). This approach generates detailed descriptions of children in a naturalistic setting interacting with our probes, in alignment with our design research agenda (Sharrock & Randall, 2004).

3.1.1. Selection and participation

Two classes of 37 children aged 3–5 years participated in the study at this site. Three sessions of 2 h were recorded over 8 weeks. The team introduced a digital manipulative technology probe, *Embeddables*, in a rural community preschool. Two preschool groups (n = 37) with children aged 3–5 years, their educators and support personnel were observed using video cameras. The research team considered how children interacted with the *Embeddables* and how digital manipulatives might be designed to support social and child-led play while building an understanding of foundational simple programming strategies and dynamic systems. The tools were laid out without any specific initial introduction. Any subsequent interventions or scaffolding of their play by the researchers/educators were opportunistic, either building on children's existing interactions or if children could not understand the technology (Hewes, 2006). Following an intervention, children were again invited to explore the tools in their free-play time. It was observed that during the sessions, 16 children played with the devices, with ten children playing with the Embeddables for an extended time (over 10 min in one sitting and consistently returning to play with them throughout the 2-h session).

3.1.2. Informed consent and data privacy

Ethics was granted (HREA6604), and initial consent from carers was sought prior to the collection of data. Consent forms were collected through the educators of the centre. Carers were provided information packs and contact information. Before the study, researchers introduced themselves to the children and explained the types of toys and how and where video would capture their movements. Images were made available to the children to show the type of data collected. Children were able to move in and out of the space freely. Before being recorded on video, all children were asked permission for their image to be captured (i.e. "Is it okay if I take a video of you?" pointing to the camera). One video camera was situated on a stand and kept to the side of the space and at a height that allowed children to view what data was collected. A hand-held camera was also used to ensure movements with the technology were captured whilst children were playing (Cutter-Mackenzie, Edwards, & Quinton, 2015). Children could ask to replay what the camera had recorded, as we wanted to support children's autonomy over their play space (Clark, Flewitt, Hammersley, & Robb, 2014). All observations were included in the corpus of data for analysis (Clark et al., 2014; Cutter-Mackenzie et al., 2015). While the study was both ethnically- and gender-diverse, comparisons between the ethnicity or genders of participants were not a focus of this study and this data was not collected. Data gathered was kept on password protected devices and consent forms were stored separately from identifiable data gathered to ensure data privacy.

3.2. Technology probe description: embeddables

Technology probes are used in design-oriented research to: elicit feedback from the field, test developing technologies and prompt exploration of future technologies (Hutchinson et al., 2003). Traditionally, technology probes are simple and adaptable systems that support avenues to understand constraints and user needs beyond the deployment of existing or fully developed technologies (Matthews, Kaiser, Lum, Moran, Richards, Bock, & Wiles, 2024). As limited research has designed CT tools specifically for preschool children, using bespoke technology probes such as Embeddables provides opportunities to learn and respond quickly from the field. Technology probes are useful in developing technologies for early childhood settings as children can show rather than verbalise their preferences in activity. Technology probes are often used in complement with traditional ethnographic methods, such as interviews and observations, to understand cultural settings (Gaver, Dunne, & Pacenti, 1999). Technology probes, like medium and low-fidelity prototypes (Hartson & Pyla, 2012), are not intended to be complete designs. Instead, they explore technological or design aspects to be interrogated before implementation in a developed prototype.

3.2.1. Overview of the design of embeddables

Embeddables (see Fig. 2) were iteratively developed and deployed as a technology probe (Hutchinson et al., 2003) to explore digital manipulatives in an early childhood classroom. *Embeddables* were designed with the following five features: 1) open-directional and multi-modal interactions (limiting perspective shifting), 2) simple conditional coding (limiting problem-solving steps), 3) limited abstract symbols, 4) a distributed system that contains proximity reactions, and 5) plush playful forms. These attributes were considered in light of our purpose, which was to design to support a better understanding of foundational coding strategies and dynamic system knowledge (Resnick et al., 1998, pp. 281–287).

Open-directional and multi-modal interactions: *Embeddables* are soft plush toys embedded with microcontrollers; they provide opportunities for children to move with the devices (i.e., cuddling, throwing and running), limiting the need for *perspective shifting*. The open range of interactions (not just of the *Embeddables*, but that children attempt with them) was implemented with the idea of expanding our understanding of how alternative interactions help children explore CT.

Proximity reactions as coded behaviour: An alternative means of enabling children to encounter a simple if-conditional coding concept was implemented in the design. Proximity reactions in the *Embeddables* were designed to be triggered by the children's likely interactions with the toy's affordances (e.g., throwing and multi-directional movement). We wanted to explore how encoded behaviours of the *Embeddables* might be understandable (and manipulable) for young children. A set of simple 'if-then-else' proximity reactions was implemented for children to discover and select depending on what output they seek to trigger (Figs. 3 and 4). The built-in behaviour was intended to reduce young children's need to remember problem-solving steps while supporting their early exposure to CT (Gerosa et al., 2021).

Limited abstract symbols: Tangible educational devices are often designed using symbols either as a programming device or to communicate to young children their purpose; studies report that young children have found it difficult to understand what communication symbols represent (Silva, Dembogurski, & Semaan, 2022; Gaver, 1991, pp. 79–84; Manches & O'Malley, 2012). By considering alternative approaches to exposing children to coding concepts, we aim to identify how other actions, interactions, and relations embedded in (and between) toys may create productive avenues for children's exposure to

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

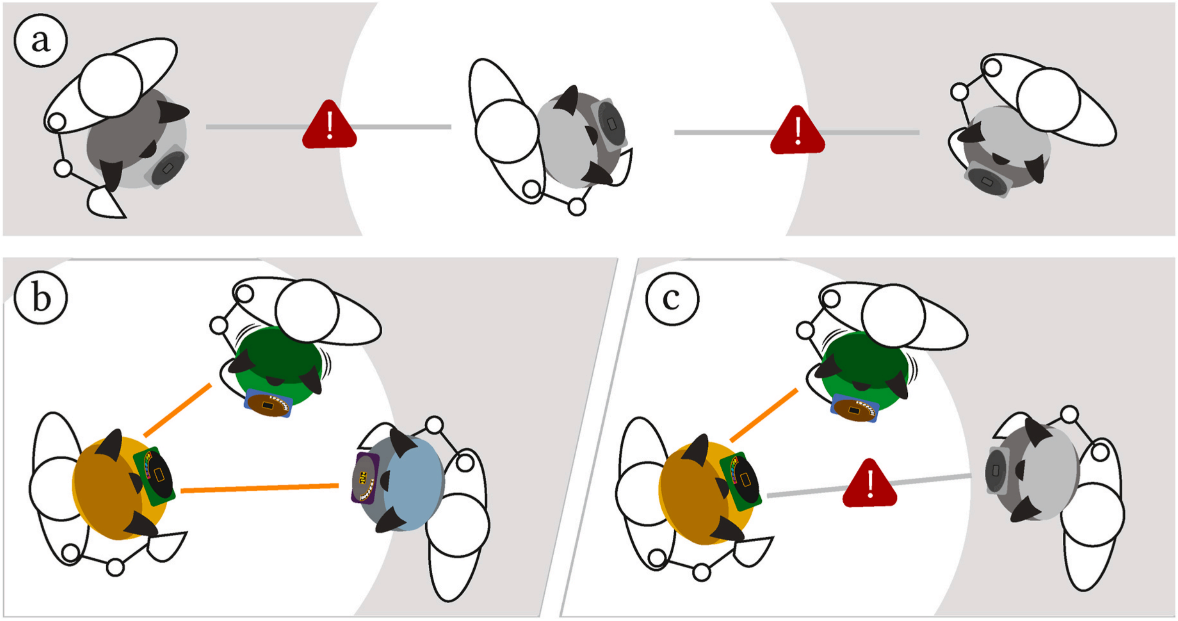

Fig. 3. The proximal reactions of the *Embeddables*. 3a) At a distance, the outputs stop working. 3b) As they come closer, the outputs are triggered (vibration, and LED array). 3c) Children can manipulate when the outputs are triggered through playing with distance. Specific outputs of each *Embeddable* are described in Fig. 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

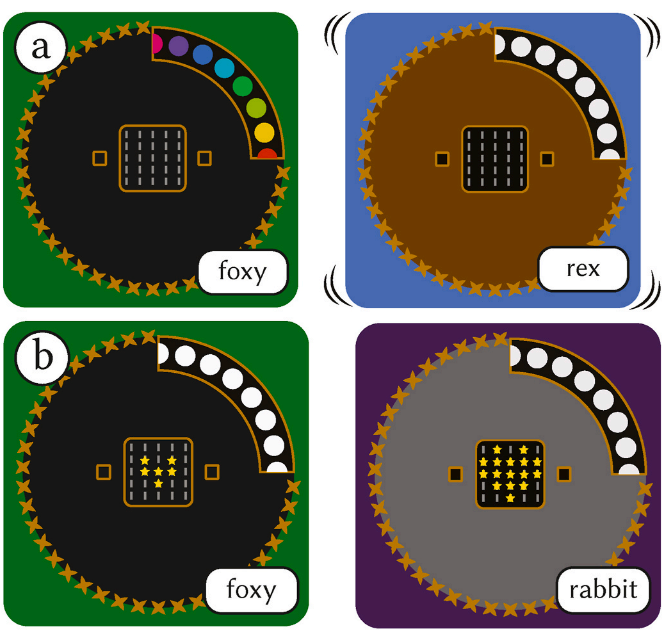

Fig. 4. *Embeddables* -foxy, -rex and -rabbit in close proximity. 4a) shows *Embeddables*-foxy and -rabbit in proximity: foxy's LED RGB lights turn on, rex's LED array and vibration motors turn on. 4b) shows Embeddable-rabbit's LED array turns on in sync with -foxy's.

CT.

A distributed system that contains proximity reactions: The digital system is distributed and responds between the manipulatives. It also is designed at a scale that encourages multi-users to engage with the devices (Bakala et al., 2023, pp. 477–486; Burleson, Harlow, & Nilsen, 2018). This allows for direct manipulation by children but also encourages social play (Vygotsky, 1980).

Plush playful forms: Animal characters were chosen to determine whether or how children would involve them in multi-modal free-play (see Fig. 2).

3.2.2. Embeddables technical description

The *Embeddables* technology probe has an outer fabric pocket that houses microcontrollers, sensors, outputs, and batteries. The pockets are either sewn in or Velcro-attached to everyday objects (in this case, plush toys). The *Embeddables* have been coded so that the outputs change depending on how close the technology probes were brought together, creating a distributed system. Plush animals were chosen to house the *Embeddables* in contrast to traditional vehicle CT robot toys and to determine how other interactions might influence children's embodied responses. More precisely, we speculated that characters (*Embeddable-rex, -rabbit, -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.

3.3. Set up observational activities

Explorations of *Embeddables* were conducted during free-play time, generally after a 'learning time' of 30 min, when teachers led children in scaffolded learning activities. During free-play time, children self-selected activities placed around the preschool. For example, inside free-play time activities included painting, constructing, and pretend play; outside free-play activities included water play, bicycle play, and sand-pit play. The technology probes were placed in a quiet indoor puzzle area. A researcher always supervised the technology probes, and educators moved in and out of the area as needed. Educators and a researcher were able to respond to children's questions and build on child-led activities but were instructed not to provide formal instruction. Children were free to remove themselves at any time and were not coerced into playing with the technology probes.

3.4. Data analysis process

The research team comprises researchers from interaction design, computer science, and early childhood education, with the first author being responsible for curating data for analysis by the team. The process of analysing video data was adapted from Jordan & Henderson's principles of interaction analysis (Jordan & Henderson, 1995) and Heath, Luff, & Svensson (2007). Captured video/audio recordings were initially logged by the first author. The video data was divided into segments into each child's or groups of children's engagement with the probes. These were analysed for outliers (novel interactions that offered possible design directions) and repetitive interactions (i.e., the same action performed by multiple children). The selected videos were then presented to the research team for more detailed analysis. Analysis sessions within the research team were conducted: the selected videos were shown along with initial transcriptions, and the team discussed the types of play being performed, what kinds of activities were being undertaken, the children's and educators' language in which they described what they were doing, and the features of the probes that supported or hindered interactions. Selected excerpts from the sessions were then transcribed in greater detail using a combination of manual and automatic transcription and imported into NVivo™ where they were then coded for their types of social interactions, play, technology interactions, and the development of digital literacy and CT skills (see Table 2). The resulting themes are presented and analysed as cases from the data, to preserve contextually situatedness of the episode, and to highlight how children develop embodied understandings of the technology from the probes and the environment.

4. Findings

Analysing the video data to determine how the technology probes were used, we observed several themes relating to the type of play activities the children undertook and how these linked to the properties of the interactions and the forms of the toys. Three main themes were identified in the data and are discussed below, including: (1) Proximity reactions triggered exploratory play episodes, (2) distributed dynamic interactions created opportunities for shared meaning-making, and (3) playful exploration enabled problem-solving with procedures and debugging. These are discussed below in relation to the features of the digital manipulatives that supported these activities.

4.1. Proximity reactions triggered exploratory play episodes

Through our observations, we saw that children would throw, shake, or roll on top of the plush digital manipulatives, which often created unexpected outputs from the devices in play. As the plush animals were thrown together, their interactions would change, causing the children to pause to watch the *Embeddables*. Initially, children were drawn to the tactile plush form of the *Embeddables* which had limited explicit controls (i.e., buttons or screens) to initially engage them. Children would start to play with them as plush toys; however, as they were using their bodies to play with the *Embeddables*, they would notice the change in the *Embeddables* output responses due to their proximal designed-in behaviour. These interactions led to further epistemic play exploration, such as placing them all together, walking away with one, and once realising it had stopped responding, moving them back so they were placed next to each other. As the *Embeddables* were placed in closer proximity this would trigger the lights to animate or the vibrations to activate (see Section 3.3.1). In multiple cases, children would then stop, look up, and invite their friends or educators into the room to discuss the interactions.

An example of this type of triggered curiosity was when Charlie (A child at the preschool), seeing that the *Embeddables* were temporarily available and scattered over the floor, came over to pick up each *Embeddable* to look at and begin to line them up next to each other (Fig. 5a). The *Embeddable-rex* vibrated, causing Charlie to look over to the educator (Fig. 5b). The child then picked up the *Embeddable*, walking it over to the educator, saying, "*I feel something in here … I feel something in here*" (Fig. 5c). The *Embeddable* stopped vibrating, and Charlie paused;

Table 2
A summary of play behaviour and learning indicators found in the children's activities with the Embeddables, adapted from Newhouse CT and digital play framework (Newhouse et al., 2017) (based on Bird and Edwards Digital Play Framework (Bird & Edwards, 2015)).

Behaviour	Function	Learning Indicators (Bird & Edwards, 2015)	Description
Object of activity: What the object does? (Epistemic play)			
Exploration	Designed in behaviour (proximity reactions) (Section 5.1)	Random use of the device.	Holding, throwing, shaking rolling on top of (Fig. 5)
	Providing ways to see inside the workings of the plush animals (without touching electronics) (Section 3.2)	Locating the operating functions of the device	Pulling the technology open to look at the different parts.
	Conditional proximal relations (Section 5.3) Abstracted multisensorial reactions but with clear feedback (Section 5.4)	Locating the operating functions of the device	Holding different parts of one Embeddable to find source of outputs (Fig. 7). Randomly moving different Embeddables around while holding another Embeddable.
	Conditional proximal relations (Section 5.3) Distributed interactivity (Section 5.2)	Seeking assistance for desired outcome	Wondering loudly why it isn't working, which encourages others to explain how the toys work. Explaining to educators what they felt from the toys (Fig. 5)
Problem solving	Conditional proximal relations (Section 5.3)	Relating actions to the response/ function	Purposeful incremental movement of the proximity reactions to get a desired response (Fig. 5)
	Conditional proximal relations (Section 5.3) Abstracted multisensorial reactions but with clear feedback (Section 5.4)	Trying different actions to solve an issue (debugging)	Pressing the arm at different levels to get the vibrations to work. (Fig. 7a). Moving other toys closer and further apart to see if they worked.
Skill acquisition	Conditional proximal relations (Section 5.3)	Intentional and deliberate use of functions for desired outcome (problem solving)	Conditional logic use to make vibrations on and off procedural planning to take turns to make each Embeddable turn on and off.
Object of activity: How it is incorporated into play (ludic play)			
Symbolic	Plush forms Distributed interactivity (Section 5.2) Conditional proximal relations (Section 5.3) Abstracted multisensorial reactions but with clear feedback (Section 5.4)	Deliberate use of device for pretend play	T-rex chasing the other Embeddables (Fig. 6b). Embeddables used in performances for others (Fig. 6c).
Innovation	Plush forms Distributed interactivity (Section 5.2) Conditional proximal relations (Section 5.3) Abstracted multisensorial reactions but with clear feedback (Section 5.4)	Creating pretend play deliberately for use of the device	T-rex chasing the other Embeddables (Fig. 6b). Embeddables used in performances for others (Fig. 6c).

the educator asked, *"Did it stop?"* Charlie nodded. The educator responded, *"… it will only vibrate when it is near Foxy, you put it near Foxy, and it will start to vibrate."* Charlie walked back over to the other *Embeddables* and placed *Embeddable-rex* with *foxy*. The *Rex* started vibrating again, and Charlie smiled back at the educator and continued to interact with *Embeddable-rex* and *-foxy* (Fig. 5d).

This example shows how a surprising moment made possible by the *Embeddables'* designed-in behaviour can trigger curiosity, leading to further exploration and questioning. The example reveals that children are interested in the causality of the vibrations even though there is no overt or obvious way to control their behaviour; it is *discoverable* and thereafter manipulable, but not a directly controllable *function*.

4.2. Distributed dynamic interactions created opportunities for shared meaning-making

The *Embeddables* provided moments of social play, which was promoted by both the manipulative's scale and the technology's distributed interactions. Children needed to coordinate their actions to understand how the technology worked (epistemic play) and then incorporate a shared mental modal of how the technologies worked to create storylines (ludic play) into their play.

In preschool, the older children (aged 4–5 years) would often play both together and individually with *Embeddables*. Initial interactions observed were often of children exploring the technology where one or more of them would cooperate to understand how the technology worked (epistemic play). After the initial exploratory period, children moved to fantasy (ludic) play where the interactions between the *Embeddable-foxy*, -rabbit and -rex were conceptualised as being a "family" or "friends" (Fig. 6a). This conceptualising of the system was often incorporated into social fantasy play. *Embeddables'* ability to be picked up and their corresponding scale were included in embodied fantasy play, as can be seen in Fig. 6b & c, when a child carrying several large *Embeddables* ran away while another child with Embeddable-rex chased after them, causing the reacting vibrations to start and stop. Likewise, in Fig. 6c, two children can be seen playing out a scenario for an audience of onlooker children. In order for the novel distributed interactivity of the *Embeddables* to be able to be incorporated into fantasy (ludic) play or performative play such as this, it must be preceded by epistemic exploration—children must first have some understanding of how the manipulatives work together.

In this example, we see that social play was promoted by 1) the scale of the tools, in that it is easy and sometimes easier for more than one child to use the digital manipulatives together, and 2) because there is a distribution of the loci of actions and reactions between the tools. No one child held control of the technology in that the children had to work together to enable the digital manipulatives to work. We can observe through the changes in play behavior from epistemic to ludic, that

Fig. 5a. Charlie picks up each *Embeddable* and looks at each one and then places them next to each other [02: 3′07].

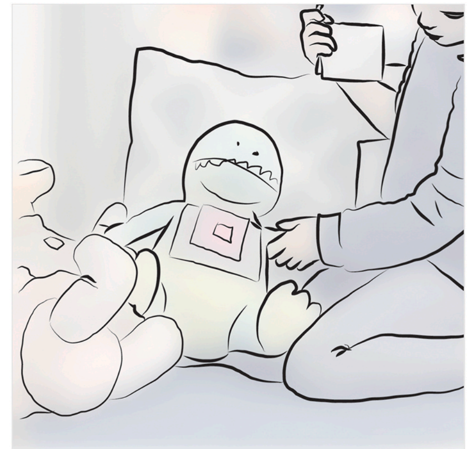

Fig. 5b. Charlie feels that the *Embeddable-rex* vibrates, and starts to locate where the vibrations are coming from [02: 4′01].

Fig. 5c. Charlie looks up and sees the educator nearby, takes the *Embeddable-rex* with them [02: 4′07].

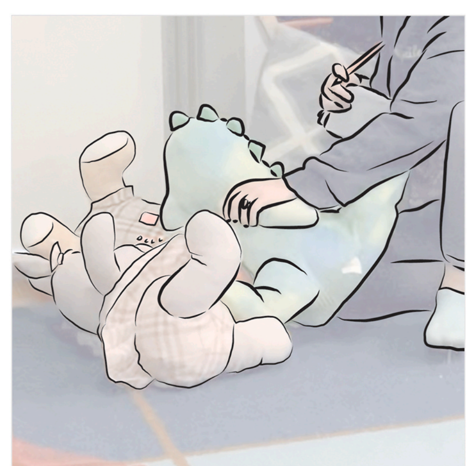

Fig. 5d. After talking to the educator. Charlie goes to confirm if the *Embeddable-rex* will vibrate again [02: 4′32].

Fig. 6a. Children conceptualise the *Embeddables* as 'friends' [D1_2′43].

Fig. 6b. Children run around with the *Embeddables* playing 'chasey' [D1_38′29].

Fig. 6c. Children playing 'make believe' with the characters of the *Embeddables* [D2_0′10].

children did start to create an understanding of how the system worked.

4.3. Playful exploration enabled problem-solving using procedure and debugging strategies

Problem-solving occurred throughout the preschool sessions. Below, we discuss how problem-solving manifested with the digital manipulatives and how it differed when problem-solving was scaffolded by the educator or led by the child.

4.3.1. Educator-extended problem-solving

Educators were often seen joining in with the children's investigative play with the *Embeddables*. When opportunities presented themselves in the children's play with the *Embeddables*, educators extended and built on existing activities (Hewes, 2006).

It was observed that educators could keep the children's attention for longer than if children were left to explore independently. Educators often incorporated games while exploring what the technology could or could not do, often discovery-type games such as iterations on hide-and-seek or guessing when interactions happen.

An example of an educator responding to a child's actions was when two children were sitting and playing with the *Embeddables* on the floor. One child - Jen, was holding the hand of *Embeddable-rex*, squeezed its hand (see Fig. 7a), and experienced the feeling of the ensuing vibrations (the vibration motor is located in the hand of the *Embeddable-rex*), whilst the other child – Tobs, was watching Jen.

Seeing that Jen was feeling the *Embeddable-rex's* vibrations next to Tobs, the educator asked, *"… so then if you take him [seeing Embeddable-fox, the other plush toy on the floor] away, does he stop vibrating?"* Jen held the hand of the *Embeddable-rex* and nodded, *"He is still vibrating, yeah!"* questioned the educator. *"Yeah"*, replied Jen. *"Yeah?"* the educator confirmed. "*Oh no, he is supposed to stop; how about that? is it stopped now?"* and moved *Embeddable-fox* further away *"yeah?"* asked the educator. Jen shook their head, smiling. The educator continued, "*No, okay, and when you bring him closer, is he going to vibrate? When does he start to vibrate? Does he vibrate now?"* Jen held onto the *Embeddable-rex's* hand and answered *"No"*. The educator stepped the *Embeddable-fox* closer still. *"Does he vibrate now?"* Jen responded. *"No"*, laughing. Again, the educator moved the fox closer, asking, *"Does he vibrate now?"* Jen looked up, smiled and said, *"No!*". The educator laughed "*Still No!*", *"Does he vibrate now?"* asked the educator again. Jen looked up and grinned "*Yes!*". The educator explained "*Yay, I could see, cause he's little love heart came on, so you can see when he starts vibrating, see? And then I take him away (pulling the Embeddable-fox away again) he's going to stop*

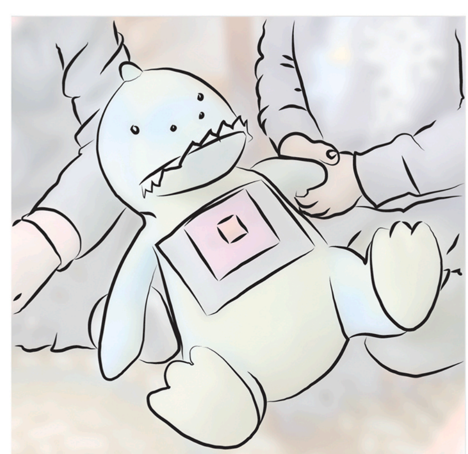

Fig. 7a. A child holds on to the *Embeddable-rex* to try and get him to vibrate again, the Educator is seen to show how the vibration is switched on in proximity of the other *Embeddables*. [D1_0′57].

soon … " Jen, still holding on to the arm, looked down at the LED array to check if the love heart was flashing. [D1_00′55].

After this interaction, Jen declared that the animals are all 'friends'; Tobs asked Jen to hold *Embeddable-rex* and feel for the vibrations, watching *Embeddable-foxy's* lights go on and off (Fig. 7b). The two children were seen playing with and hugging the three animals together. Jen was observed telling their classmates how to get the *Embeddables* to 'turn on' by placing them near each other, explaining their new understanding of how the *Embeddables* work together.

In this example, we see that the conditional proximal relations between the artefacts supported the educator as they played with the child in a way that encouraged further understanding of what could be done with the technologies and how the reactions were triggered through being proximal to the other *Embeddable*. The educator encouraged a deeper (or functional) understanding of how the technologies worked together, scaffolding simple CT practices of articulating a problem 'what happens when?' and then proceeding with an iterative step-wise problem-solving strategy by seeing when and how the interactions are triggered and at what distance, articulating the differences between the whole and parts of a system.

4.3.2. Child-led problem-solving

From the above examples, we can see that children could undertake their own explorations with and without support to understand how the whole and parts of the *Embeddables* worked as a system. We also observed situations where children played with the *Embeddables* to achieve a desired outcome (simple conditional programming) by procedurally testing when reactions occurred (see Fig. 7a and b). When unexpected reactions happened, they were able to debug things like why it was vibrating rather than displaying lights. There were some things we did not observe. Once children understood how the system worked, they did not appear to develop further critical reflection on how the technology worked or how its interactions could change. For example, we did not see children engage with the proximity reactions incorporating time as a variable, e.g., by moving one *Embeddable* nearer and farther, just across its proximity threshold and back, it is possible to make the lights look like a siren or create on-off patterns with the vibrations. This is behaviour we didn't quite see. Such lack of child-led extended problem solving could be due to several factors, such as the inbuilt interactivity (lights and vibrations) are not as dynamic or autonomous as expected or that time is required for the children to assimilate the technologies to discover other ways to manipulate their reactions. This may require further exploration or exposure over longer time periods. The *Embeddables* did not appear to develop further critical reflections on how the technology worked. Initial feedback from the children included suggesting greater incorporation of sound and vibration reactions; this complements our observations of how children gravitated to the multisensorial outputs.

Fig. 7b. A child brings the *Embeddables* together to see if they can make the rex vibrate. They are then seen to show other children how the *Embeddables* work [D1_2′43].

In summary, the epistemic (explorative and problem-solving) play of the digital manipulatives was observed in children's social and individual free play, which extended into fantasy (ludic) play with the devices. Several qualities of the digital manipulatives influenced how students and educators were prompted to set local problems and find solutions. These qualities supported initial interest, social play, and gaining experience in some foundational digital literacy practices. Our discussion focuses on particular design features of the *Embeddables*, namely their conditional proximal relations between artefacts, distributed interactivity, and the designed-in behaviour (rather than controls).

5. Discussion

In this paper, we have set out to understand how digital manipulatives might be designed to support social and child-led (aged 3–5 years) play while building early exposure to CT. Embodied cognition theory has sharpened our attention to the bodily interactions that are components of children's developing understandings of the technology. Our review of the literature indicates that at this age, young children often learn through physical play in informal environments and may not be developmentally ready for toys that incorporate perspective shifting, abstracting meaning from symbols, or multiple-step processes that many existing tangible CT technologies embody. However, children can understand other foundational CT practices, such as social associative and cooperative play, cause and effect, how to debug, and procedural thinking, some of which are currently taught to young children in unplugged activities. While this is promising, unplugged activities have been found challenging for children to transpose into digital worlds (Grover & Roy, 2013).

Our technology probe incorporated simple proximal coding into a system of plush toys that children could physically manipulate. Our observations identified several themes relating to the type of activities (CT and play) the children undertook, such as exploratory play episodes, shared meaning-making using distributed dynamic interactions, and problem-solving with procedures and debugging. From the above themes, we analysed the features of these digital manipulatives that support CT and play activities: designed-in behaviour, distributed interactivity, conditional and proximal relations between artefacts, and abstracted multisensorial reactions. These four design features are discussed in relation to an embodied cognition lens and existing literature and their impact on designing digital manipulatives for early childhood education.

5.1. Designed-in behaviour versus explicit controls

Curiosity and inquiry are essential dispositions for children to take ownership of their education (Montessori, 1963). Current empirical studies have little to say regarding how this might be enacted in the design of digital toys to support children's ability to be exposed to digital literacy. This is surprising, considering the importance of curiosity and creative play in early childhood education curricula (ACECQA, 2022; Lee et al., 2023; McPake, Plowman, & Stephen, 2013), and exposure to digital literacy (Brennan & Resnick, 2012, p. 25; Lee et al., 2023; Schneider & Blikstein, 2018). Our findings suggest that CT tools were able to promote curiosity about how the technologies worked through 'surprising' features such as the designed-in behaviour (rather than functionality), which encouraged children's further exploration. The technology probe *Embeddables* did this using animated outputs (lights/vibrations, etc.), which could only be triggered by surreptitious or otherwise discoverable means and then only reacted to other parts of the system (i.e., the other manipulatives). This led to children asking 'why?' and trying to reconstruct their actions to trigger the same output again carefully (Bird & Edwards, 2015; Matthews & Matthews, 2021). Designed-in behaviour is fundamental to the physicality and understanding of implicit cause and effect of digital systems, creating a different set of opportunities through play than other more explicit digital interactions, such as co-located cause-and-effect controls like buttons or switches.

5.2. Distributed interactivity and outputs

Collaboration is a skill that supports complex problem-solving (Lai, Ye, & Wong, 2023). Research has often reported that traditional tangible tools for digital literacy resist young children's efforts to collaborate or socialise when used (Burleson et al., 2018). The singular robot-child interactions provide for one child and one device, leaving educators to encourage group activities that result in one child operating and others in more passive roles or discarding the activity to participate in more socially engaging activities (Odgaard, 2022; Lai et al., 2023). This has prompted researchers to consider how tools can facilitate activities that encourage collaboration and education of technology systems (Burleson et al., 2018). Odgaard (2022) proposed that social objectives must be considered in concert with the design of learning activities for young age groups. Although most research into the design of collaborative devices has been conducted in older children, these have led to interventions that have carefully considered the physical scale of the design, such that no child is physically able to have complete control over the technology (Alissa, 2007, pp. 195–202). Our study found that scale paired with distributed interactivity contributed to young children working together on problems or playing with the devices. Distributed interactivity includes the distribution of the location of actions and reactions throughout the system. This means that multiple children can control the different technologies in the system and communicate or maneuver their digital manipulatives for a shared purpose.

5.3. Conditional, proximal relations between artefacts

The development of instruction-giving as a skill is multi-faceted, requiring some understanding of procedure, symbolic language, and the ability to take another's perspective. Children need to be exposed to and scaffolded into these strategies at certain points in their development process (Gerosa et al., 2021; Hewes, 2006). In our case, the implementation of simple conditional proximal relations supported children in beginning to have access to a system they could (partially) manipulate and control. But proximal reactions were a design choice that determined the embodied scale of the system—reactions could not be manipulated except at a greater-than-child scale, yet reactions (feedback) could be seen/confirmed at a distance by changes in the other manipulatives' LED displays. From our findings, the system's ability to provide timely feedback at a distance supported children's ability to debug and iterate through what the *Embeddables* could or couldn't do. Prior research into the importance of solving problems with both technology and coding has been conducted in the first years of primary school as a scaffolded activity (Matthews, Viller, & Boden, 2020, pp. 511–518; Silvis, Lee, Clarke-Midura, & Shumway, 2022). Our study likewise found that problem-solving happened in free play and was an important activity for children's understanding of the technology and what could be done with it.

5.4. Abstracted multisensorial reactions but with clear feedback

One of the ways that *Embeddables* embody an alternative approach to the design of digital manipulatives for preschool children is how they implement abstracted, multi-sensorial reactions with clear feedback (Antle, Droumeva, & Ha, 2009, pp. 80–88). The reactions were *abstracted* in the sense that there was no direct or obvious connection between the action with one toy that triggered light and/or vibration reaction in another. This sits somewhat uncomfortably with existing guidelines for tangibles where explicit mappings are prioritised (Antle et al., 2009, pp. 80–88; Manches & O'Malley, 2012). In our data, this was a feature that appeared to invite children's reactions and further interactions (and with respect to the vibration reaction, their delight). This indirect or abstracted connection between the *Embeddables* created observable possibilities for surprise, discovery and exploration that a more direct mapping of controls is unlikely to reproduce. It also prevented there being a right or wrong way to play with the system, which may have been partly responsible for the extent to which we saw children developing their own forms of play with the *Embeddables*. In any case, this type of design choice is one that has not been widely explored in digital toys for young children but may have greater potential than previously acknowledged.

5.5. Designing for balance between play and skill development for CT

Play is critical for young children's learning and development, promoting exploration and understanding through their environment. As digital technologies become more entrenched in young children's lives, it is important to offer opportunities that foster an active problem-solving process with digital toys to promote an emerging understanding of computational thinking (Jeannette, 2011). This approach is similar to how children process reading, writing, and mathematics in early childhood (Erstad & Gillen, 2019). As previously discussed, most tools that provide for problem-solving with digital technologies use methods that can be problematic (see Section 2.1), leading to adult-led formalised activities. Table 2 summarises the observed play behaviours with the technology probes (adapted from Bird and Edwards' (2015) Digital Play Framework for early childhood environments) and incorporates the functions of the devices that supported the types of play observed.

In this study, we used a technology probe to discern if some functions, such as proximal behaviour and distributed interactivity, would create opportunities in play that would also promote exploration of the technology and how it worked. From our literature review and the lack of knowledge regarding different types of manipulatives to explore CT, we held no expectations of what the children could learn from our probes with respect to computational thinking skills such as programming or step-by-step procedural problem-solving. However, we did expect to see children purposefully use the toys to demonstrate knowledge (digital literacy) of how the simple behaviours of the technology worked. In some essential respects, our technology probe successfully showed that children were curious, wanted to know about the toys, and could incorporate simple behaviour, i.e., conditional interactions, into play. However, we are only beginning to determine what skills children can acquire or display in play. Our method of using technology probes was useful in obtaining observational data about their ability to plan procedurally and use conditional logic (see Table 1). However, technology probes are not complete designs, and more work is required to determine if toys can also support pattern development (algorithms) and symbolic language use in play (see Table 1). The findings presented in Table 2 highlight that although initial exploring with the devices was incorporated into ludic (fantasy) play (see Fig. 6b & c), further skill development is missing from our observations. For example, we would like to see iterative skill building with digital tools, to see children 'programming' increasingly complex behaviour in the toys through their play. Our study represents a formative step in understanding the balance between play and skill development with digital literacy tools.

5.6. Limitations

There are limitations to this study. First, the sample diversity requires expansion; although this study was conducted at a single preschool, enabling a longer-term engagement (over 8 weeks), additional studies with more diverse early education centres would be required to determine the longevity and progressive outcomes. Second, to our knowledge, only a few studies have looked at the design of existing digital toys for CT from a child-led, free-play perspective in early childhood environments. Although work has been conducted with unplugged free-play activities such as block building (Ehsan, Rehmat, & Cardella, 2021), and researchers cite educators as incorporating digital manipulatives in free-play (Harper, Caudle, Flowers, Rainwater, & Quinn, 2023; Quinn, Caudle, & Harper, 2023; Roussou & Rangoussi, 2020, pp. 31–44), there is not yet enough data to clearly articulate what children aged 3–5 years can already do and not do with existing digital toys in free-play, and what (other) gaps digital manipulatives might fruitfully address. Third, a control group would add validity to the idea that exploring alternative CT tangibles would provide a further understanding of their impact on knowledge acquisition in digital literacy.

5.7. Future work

Future work will focus on children's activities in free play with existing built-for-purpose digital toys and novel technology probes such as *Embeddables*. Based on the understanding gained in this initial study, we intend to further iterate on the *Embeddables* with educators. Hence, the tools will evolve to embody more complex behaviour as children learn. Further phases include evaluating iterations of the technology probe in formal education environments.

6. Conclusions

In this study, we have designed a digital manipulative to support an understanding of foundational problem-solving strategies and dynamic system knowledge in early childhood (aged 3–5 years) deployed as a technology probe. Our analysis highlights underexplored design opportunities in developmentally appropriate digital manipulatives to support young learners in taking small but essential knowledge leaps in digital literacy. Current digital toys for CT purposes (often vehicle robots) used in preschool employ symbolic representation, explicit controls, and multiple-step coding in their features. When young learners are not developmentally ready to learn these more formal coding methods or are only exposed to interfaces that encapsulate directional programming, opportunities are missed to explore alternative interfaces that support emerging understandings of digital devices that may be more developmentally appropriate.

Our study allowed us to analyse how children played with and made sense of the novel physical programmable technology probes, leading us to unpack some of the specific features of these tools, such as conditional and proximal relations between artefacts, multisensorial reactions, distributed interactivity, and designed-in behaviour. Our early design interventions have been observed to lead to promising learning experiences with, through and about digital technologies for preschool children. Continued development of technologies that are informed by other types of computational thinking paradigms, such as embodied cognition, reveal design alternatives to classic emphases on abstract representations and formal rules; these developments show potential for profoundly affecting how children experience and understand technology and its capabilities.

CRediT authorship contribution statement

Sarah Matthews: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria Nicholas:** Writing – review & editing. **Louise Paatsch:** Writing – review & editing, Supervision. **Lisa Kervin:** Writing – review & editing, Supervision. **Peta Wyeth:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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